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FLIGHT MEASUREMENTS OF ISOLATED THERMALS

by

Betsy Woodward

FINAL REPORT

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Contents

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INTRODUCTION

A glider has been used to study atmospheric thermals. Traverses were made through individual thermals while readings of airspeed, rate of climb, attitude, time, altitude, dry bulb temperature and wet bulb depression were recorded on cine film. From these readings a cross-section of velocities, temperature and moisture content was obtained.

The object of the research was to obtain an idea of the magnitude of the above quantities, to evaluate the aircraft and techniques used and compare, if possible, the observed values with those predicted by various models, notably the isolated thermal model.

Note concerning this report

The purpose of this report is to present the results from those flights which have been sufficiently analysed and to give a summary of the techniques employed. It should not be considered a scientific paper. Comparison has been made between the results and the isolated thermal model primarily to indicate how the data may be applied. The writer would prefer not to draw conclusions until discussion and further analysis can be done.

Equipment and techniques used and a decription of the isolated thermal model are summarised only. A full discussion on the use of gliders in the investigarion of atmospheric thermals is presented in the first Annual Report, 28 February 1961. "Experiments on convection of isolated masses of buoyant fluid" (J. Fluid Mech., 2, p.583, 1957) by R. S. Scorer gives a description of the results obtained from laboratory experiments; "The motion in and around isolated thermals" (Quart. J. R. Met. Soc., March 1959) by B. Woodward presents the velocity field, and "A theory of thermal soaring" (Swiss Aero Revue, 6, 1958) by B. Woodward gives an example of the effect upon a sailplane spiraling in an isolated thermal.

Summary and evaluation of equipment and technique

A small cumulus was used as a marker while the glider made passes through and below it while attempting to maintain constant attitude. On some occasions a circling glider was used as a marker. During the last two weeks of field operations two gliders were employed and various flight technique tried. To date the data obtained from only one aircraft have been analysed; the second, which was primarily used as a reserve, did not carry temperature instruments and on many flights the recording camera jammed.

The primary glider, a 2-seat Slingsby Eagle, was owned by the Royal Air Force Gliding and Soaring Association and was operated from R.A.F. Andover and from Lasham Airfield, both situated in Hampshire. A member of the RAFGSA flew the aircraft ; the Principal Investigator was observer on all flights, taking notes and operating the recording camera.

The arrangements with the RAFGSA and its members were most satisfactory. The glider is normally used for advanced training; exclusive use of the machine was had during field operations.

Ground observations, conducted by Dr. John Rushforth during the 1961 investigations, included obtaining winds aloft (tail balloon, single theodolite) and operating a ground time lapse camera. The latter was used to record the development of the cumulus under which the glider was flying. The film, Kodak - negatively developed, from the Andover expedition was satisfactory. Unfortunately the film, Ilford - positively developed, from Lasham is overexposed and barely readable. No concentrated effort has yet been made to interpret this film which includes the cumuli described later in this report.

The Bolex time lapse camera which recorded the glider instrument panel every half second was satisfactory; failure occurred twice during the two years. This film was subsequently projected by a high quality film reader and the instrument readings, eight in all, were noted. It took one to two minutes to read each frame.

A considerable amount of data was reduced by hand before a program for an electronic computer was completed. The readings from the film were subsequently punched on tape, after correcting for instrument error where necessary, and reduced by machine. The computations were carried out on a Stantec Zebra computer installed at Queen's College, Dundee, Scotland and the programs were written in an auto code. Dr. J. Rushforth, Dept. of Mathematics, Queen's College, wrote the programs and operated the machine. Two programs were written for the velocity data; the intermediate program, where an averaging process was being carried out, took twenty minutes for a run of about ninety seconds. The results, which were on paper tape, were re-read into the machine for the calculations in the final program which took a slightly shorter time.

Data obtained from 1960 were primarily used to evaluate the flight technique and some of these were presented in the 1st Annual Report. Temperatures were not recorded. During the three-week 1961 investigations, flights were made whenever possible, however suitable conditions were encountered on only three days. Six flights on two of these days are included in this report. A seventh, and a flight on the third day, have been reduced but have not been sufficiently analysed for presentation.

The Principal Investigator has been the only full time employee on the project. During the field operations a total of about six persons, at any one time, participated. The writer is greatly indebted to these participants who donated their time and experience for basic expenses only.

In general it is felt that the aircraft and techniques employed have been a success. The most time consuming task throughout has been the measurement and reduction of horizontal velocities and the final results are still not considered satisfactory. The accuracy of both horizontal and vertical velocities is limited by the ability to measure the attitude of the aircraft. A more sophisticated instrument than the surplus artificial horizon should perhaps be used for future experiments. It is felt that the glider is the most satisfactory tool for an inexpensive and exploratory study of atmospheric thermals. If a larger investigation is conducted in the future it would be worthwhile to utilise a light aircraft which could make traverses above and below a circling glider.

Acknowledgements

The writer would like to thank all those who assisted in the studies during the past two and a half years. She is indebted to Professor P. A. Sheppard, Dept. of Meteorology, Imperial College, London and to members and staff of the Department, in particular Dr. J. Green and Dr. F. Ludlam; members of the Imperial College Gliding Club, notably Mr. K. J. Bignell and Mr. Paul Minton; the Royal Air Force Gliding and Soaring Association and members Group Captain R. R. Goodbody, Squadron Leader J. Brownlow and Sergeant A. Gough; Lasham Gliding Centre; and members of the Dept. of Mathematics, Queen's College, in particular Dr. J. Rushforth.

PART II

FLIGHT EQUIPMENT, INSTRUMENTATION AND DATA DEDUCTION

The equipment and instruments used have been described in previous reports. A short summary follows:

Aircraft

Glider: A two-seat Slingsby T-42 Eagle was used which carried a pilot (rear seat) and observer (front seat) on all flights. The "all-up weight" of the aircraft was about 540 kg. The performance figures quoted by the manufacturer were altered slightly to give more realistic values for the induced and profile drag coefficients. A sinking speed of 0.85 m/s at a forward speed, for maximum glide angle (or minimum drag coefficient), of 23.5 m/s was selected.

Tow Plane: An R.A.F. Chipmunk was used when the field investigations were conducted at R.A.F. Andover; one of three Austers, operated by the Lasham Gliding Society, was used when at Lasham Airfield.

Camera Equipment:

Bolex: A 16 mm Bolex, with a "home-made" time lapse mechanism, which was fitted in the R.A.F. Eagle, photographed the instrument panel every half second.

G.G.S. Recorder: This 16 mm, 25 ft. roll, surplus "gun-camera" was fitted in the Imperial College Eagle.

Flight Instruments

Airspeed: Kelvin Hughes Type 220-02, which gives a range of 10 to 80 mph and has a time constant of 0.5 to 0.7 seconds.

Variometer: The rate of climb indicator used was a Crossfell Variometer with a time constant of 0.5 seconds. This instrument indicates rate of change of aircraft static pressure by measuring the direction and magnitude of the airflow in and out of a ½ litre vacuum flask connected to static. The airflow causes differential cooling of two thermistor beads placed near a heated element, and the change in electrical resistance of the beads mounted in a wheatstone bridge, drives a moving coil meter through a low gain transistor amplifier. The instrument reliably indicates an airflow of ½ cc per minute. The range is -4.0 to + 4.0 m/s or -8.0 to +8.0 m/s on the 2 x scale.

Artificial Horizon: Surplus German instrument that could be read to the nearest 0.5 degree.

Altimeter: Standard sensitive altimeter with 35,000 ft. range.

Clock: 8-day aircraft clock.

Compass: E - 2 compass.

Dry Bulb Temperature: Thermistor Bridge, made by E.M.G. Hand-made Gramophone Ltd. according to specification. It has a range -2.5° to $+ 22.5^{\circ}$C on six scales.

Wet Bulb Depression: This instrument, which consists of series of 20 junctions mounted in a perspex frame, was designed and constructed by K.G. Bignell and Betsy Woodward. A number of phototypes were tested in the wind tunnel at the Dept. of Meteorology, Imperial College. The amplifier was made, according to specification, by E.M.G. Hand-made Gramophone Ltd. The difference between wet bulb and dry bulb temperatures was indicated on a 0-2 voltmeter with full scale deflection equal to 5.0°C.

The following table lists the notation, accuracy, etc. of the instruments read from the cine film of the instrument panel:

Instrument	Notation	read to nearest	instrument correction	Accuracy (rel.)(abso)	Notation after cor.
Airspeed	V_{imph}	0.2 mph	not applied	$\pm$ 0.6 mph	V_{imph}
Variometer	v_i	0.05 m/s	$1.2 \times v_i$	$\pm$ 10%	v
Horizon	Λ_{mm}	0.25 mm	1mm = 0.034 radians	see notes	Λ
Altimeter	H_{ft}	5 feet	not applied	$\pm$ 10ft $\pm$ 20ft	H_{ft}
Dry Bulb Temp.	t_{di}	0.25°C	variable	$\pm 0.02^{\circ}$ $\pm 0.03^{\circ}$	t_d
Wet. Bulb Depres.	$(t_d-t_w)_i$	0.05°C	variable	$\pm 0.025^{\circ}$ $+0.10^{\circ}$	(t_d-t_w)
Clock	t	0.025 sec.			
Compass	head.	5 deg.			

Notes Concerning Calibration and Correction for Instrument Error

Airspeed: Calibrated just prior to field investigations at R.A.F. Boscombe Down and afterwards by Kelvin Hughes, Basingstoke. In the range 50 - 65 mph the correction to be applied was always less than 0.5 mph. Correction due to position error in this range is negligible. Total correction for position and instrument error is always less than ± 0.6 mph in the speed range in which the glider was flown.

Variometer: Calibrated prior to field investigations by Peter Davey, designer of the Crossfell. This calibration showed the instrument to be under-reading by 0 to 15% at 16°C. The sensitivity varies with the temperature of the airflow, increasing as temperature is decreased by 0.5% per 1°C. At 8°C the scaling would be 4% high. The variable correction for scale and temperature, that was obtained from the ground calibration supplied by the designer, was not applied. From the flight data obtained the variometer reading was integrated and the result compared with the change in the altimeter reading. Portions were selected which had a duration of at least 30 seconds and where the glider was continuously ascending or descending. The average of 22 cases when the glider was descending showed that a scale correction of 1.19 times the indicated value should be applied. (The range was between 1.07x and 1.30x.). The average of nine cases when the glider was ascending showed an average scale correction of 1.18x (range 1.10x to 1.29x). It was decided to apply a constant correction of 1.2x the indicated value. It is reasonable to assume that the corrected variometer reading is accurate to at least ± 10% (but never greater than ± 0.1 m/s).

Altimeter: Calibration by Kelvin Highes showed that from 0 to 6000 ft the indicated reading was always within 15 feet of the true pressure height and that the difference between up and down readings did not exceed 20 feet. A correction was not applied.

Artificial Horizon: It was necessary to convert the arbitrary scale of millimetres, read from the projected film of the instrument panel, into degrees or radians of aircraft attitude. During the field operations the tail of the glider was raised and lowered, on the ground, to known angles while the change in the position of the artificial horizon was photographed. Flight tests were made late one evening in "still air", however this was one of two times when the recording camera jammed, so few of the results could be used. The 1961 ground calibration differed by a factor of 2 from the

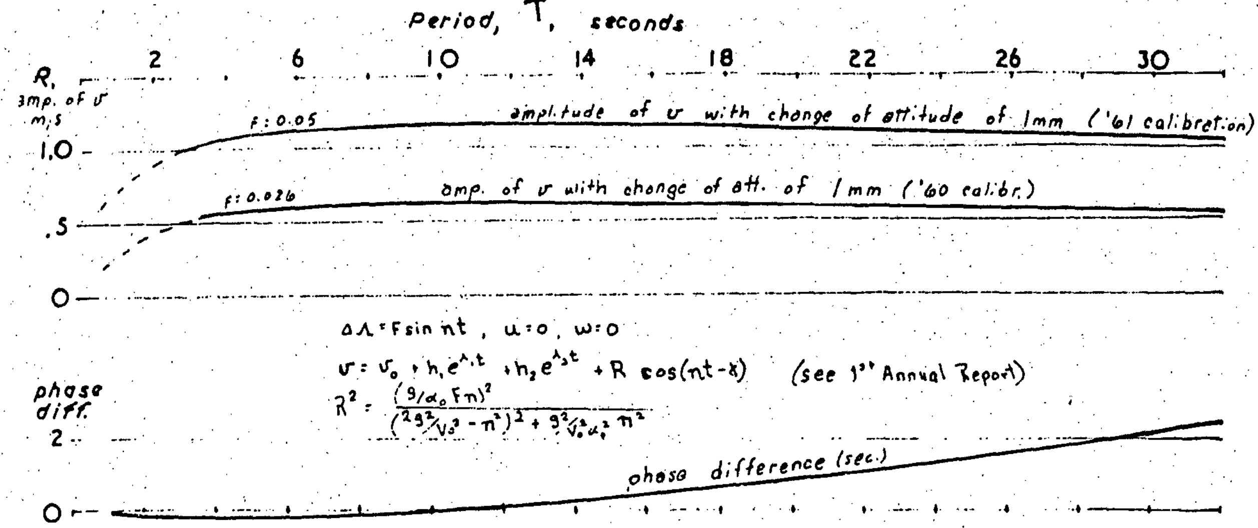
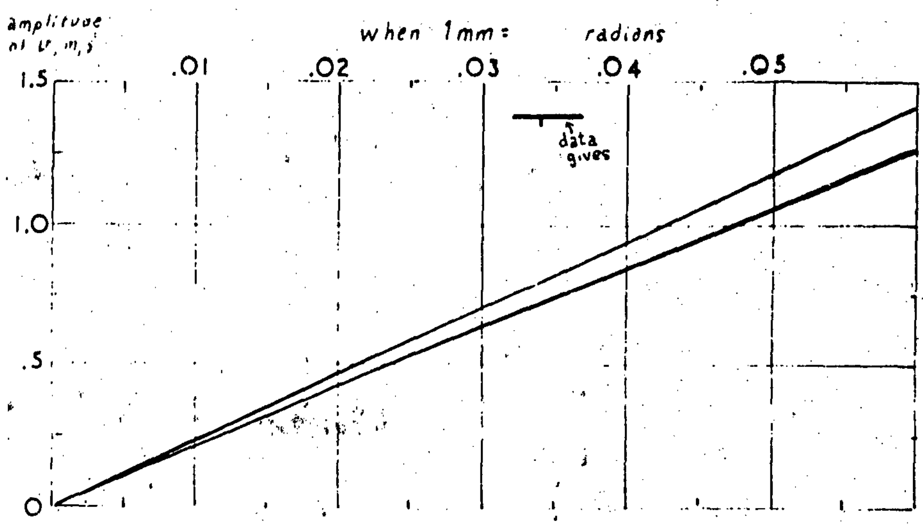


Fig. 1a



Amplitude of v when amplitude of $\Lambda = 1$ mm (valid for wave lengths ≈4-30 seconds)

1960 calibration: 1 mm = .026 r

1961 " : 1 mm = .050 r

average of flight data gives: 1mm =.

Fig. 1b

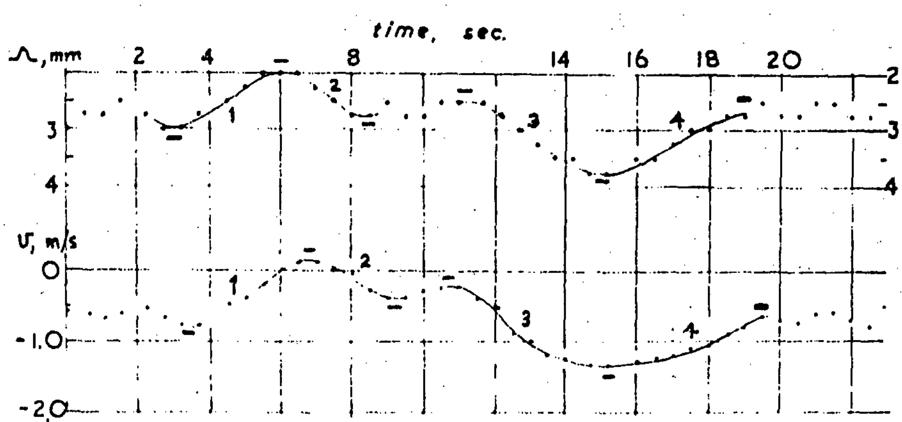


Fig. 1c

case	approx. wave length sec.	$\Delta\Lambda$ mm	Δv m/s	approx. phase diff. sec.	if a Λ th
1	12	1.0	.9	-.5	
2	8	.75	.5	-.8	
3	16	1.25	1.1	0	
4	18	1.25	.7	-.5	

calibration obtained the previous summer. Although a different instrument was used in 1960 they were both the same size and the 1961 calibration was thrown in doubt. It was then decided to obtain a conversion factor based upon actual flight data. A given change of attitude produces a change in the vertical velocity of the glider that, for all practical purposes, is not dependent upon the period of the attitude change (see Fig. 1a). Twenty four cases of attitude and vertical velocity changes were then selected from flights made on 6 July and 18 July. (The portions selected were those where there was comparatively little change in airspeed and where the change in vertical velocity of the glider appeared to be due to a change in attitude). An example is shown in Fig. 1c. The wavelengths of the 24 cases varied from 6 to 24 seconds and the average, for each day, showed that the conversion factor should be $1.0\,\Lambda_{mm} = 0.032$ to $0.037\,\Lambda_{radians}$. A factor, $C_{A} = 0.034$ was selected and is probably correct to within $\pm$ 25% for these two days.

This conversion factor is also dependent upon the state of the battery operating the artificial horizon. Moreover when the attitude of the aircraft is altered and then returned to its original angle the artificial horizon does not always return to its original position. There is also a slow drift in the instrument. These problems, and their effect upon the reduced vertical and horizontal wind components will be discussed later.

Dry Bulb Temperature: Calibrated by the Principal Investigator at the Dept. of Meteorology, Imperial College during a period of one month after the field operations. The relative accuracy (e.g. on any one pass through a thermal) can be taken as $\pm$ 0.02°C and the absolute accuracy (e.g. comparing temperature of 20°C with 8°C) as $\pm$ 0.03°C.

Wet Bulb Depression: Calibrated by Principal Investigator at Dept. of Meteorology, Imperial College during a period of one month after the field investigation. A small re-circulating wind tunnel, where the moisture content of the air could be kept constant for a reasonable length of time, was used for the calibration. There is a slow drift in the zero setting of the instrument with time. The relative accuracy of readings taken during any one run is $\pm$ 0.025°C when the change is less than about 2°C and $\pm$ 0.05°C when the change is greater than 2°C. When comparing the absolute value of readings obtained at the beginning and end of a two hour flight the accuracy would be $\pm$ 0.1°C.

REDUCTION OF DATA

From the above instruments we wish to obtain values for the following:

	Notation	Units
Dry Bulb Temperature	t_D	$^\circ C$
Dry Bulb Potential Temperature	θ_D	$^\circ A$
Wet Bulb Temperature	t_W	$^\circ C$
Virtual Potential Temperature	θ_V	$^\circ A$
Mixing Ratio	MR	grams/kilogram
Relative Humidity	RH	%
Vertical Wind Velocity	W	m/s
Horizontal Wind Velocity	U	m/s

Reduction of Temperatures

Portions of a flight where temperature data only was obtained (i.e tow, descent, spiralling in thermal) were handled separately from those portions where velocities were also required (i.e. pass through thermal).

The desired values of temperature and humidity, etc. were computed from the following formula (from Handbook of Meteorology, 1945 and Smithsonian Meteorological Tables, 6th Edition, 1951).

The dry bulb was corrected for instrument error from the indicated reading t_{di} to t_d by hand calculation. Then further correction for airspeed gave $t_D = t_d - (0.00868\ V_{imph})^2$. Then

$$T_D = t_d + 273.16 = \text{dry bulb temperature, } ^\circ A$$

$$T_W = T_D - (t_d - t_w) = \text{wet bulb temperature, } ^\circ A$$

$$T_V = T_D \frac{1 + 1.6w}{1. + w} = \text{virtual temperature, } ^\circ A$$

$$\theta_D = T_D \left(\frac{1000}{p}\right)^{0.286} = \text{dry bulb potential temperature, } ^\circ A.$$

$$\theta_V = T_V \left(\frac{1000}{p}\right)^{0.286} = \text{virtual potential temperature, } ^\circ A$$

$$MR = 1000w = \frac{0.62197e}{p - e} = \text{mixing ratio, gr/km.}$$

$$RH = {}^{e}/_{e_s} = \text{ralative humidity.}$$

where

$e = e' - \Delta e = e' - 0.00066(1 + 0.00115\, t_W\ \ p(t_d - t_w)$ = vapour pressure

e' = saturation vapour pressure at wet bulb temperature.

e_s = saturation vapour pressure

$$\ln \frac{e_s}{6.105} = 25.22 \frac{T_D - 273.16}{T_D} - 5.31 \ln \frac{T_D}{273.16}$$

(For e', replace e_s by e' and T_D by T_W

and

$$p = p_o \left(1 - \frac{\beta H_{ft}}{T_o}\right)^{g/R\beta} = 1013.2 \left(1 - \frac{.0019812\, H_{ft}}{288}\right)^{5.256}$$

= pressure, millibars

The following quantities were printed out: time (hrs., min., sec.), pressure height (metres), pressure (millibars), dry bulb temperature, dry bulb potential temperature, virtual potential temperature, T_V-T_D, wet bulb temperature, mixing ratio and relative humidity.

On some occasions the wet bulb potential temperature was obtained, from a large scale tephigram, using a combination of Θ_D and MR or t_d, t_W and pressure. The value obtained, Θ_W, is correct to $\pm$ 0.1°C.

The following table gives the changes in Θ_D, Θ_V, etc. due to changes in height, temperature, wet bulb depression, etc. (in the range of conditions in which the values were obtained).

		PRODUCES CHANGES IN				
change in	of	Θ_D °C	Θ_V °C	MR gm/km	t_D °C	t_W °C
airspeed	$\pm$ 1 mph	$\mp$ 0.01	$\mp$ 0.01	.00	$\mp$ 0.01	$\mp$ 0.01
pressure height	$\pm$ 10 feet	$\pm$ 0.03	$\pm$ 0.03	.00	0.00	0.00
t_D	$\pm$ 0.02°C	$\pm$ 0.02	$\pm$ 0.02	$\pm$ 0.01	$\pm$ 0.02	$\pm$ 0.02
$(t_d - t_w)$	$\pm$ 0.05	0.00	$\mp$ 0.01	$\mp$ 0.04	0.00	$\mp$ 0.05

Assumed accuracy (to nearest 0.05)

	Θ_D	Θ_V	MR
on runs	± 0.05	± 0.05	± 0.05
on soundings	± 0.10	± 0.10	± 0.15

Reduction of Velocities

The horizontal and vertical wind components (U and W) were obtained from the following equations:

$$W = C_D\left(\frac{\alpha_o V_i}{g}\frac{dv}{dt} - \frac{2\alpha_o V_i}{V_o}(V_i - V^*) - V_i(\Lambda - \Lambda^*) - \frac{V_i}{V_o}v_o + v\right)$$

$$U = C_D\left(\overline{V} - V_i + \frac{g}{V_i}\left[\frac{\alpha_o V_i}{g}(v - v_o) + \sum_{t=o}^{t=t} - \frac{2\alpha_o V_i}{V_o}(V_i - V^*) + \sum_{t=o}^{t=t} -V_i(\Lambda - \Lambda^*)\right]\right)$$

or

$$W = C_D\left(L - M - N - \frac{V_i}{V_o}v_o + v\right)$$

$$U = C_D\left(\overline{V} - V_i + \frac{g}{V_i}\left[\frac{\alpha_o V_i}{g}(v - v_o) + \sum -M + \sum -N\right]\right)$$

where

$C_D = \frac{\rho_{1000\ mb}}{\rho}$ = correction for density (based on standard atmosphere)

V_o = speed for minimum drag coefficient = constant = 23.5 m/s

α_o = angle of incidence at speed for min. drag coef. = const. = 0.135 radians

v_o = vert. vel. of glider " " " " " " = const. = -0.85 m/s

g = 9.81 m/s^2

V_i = indicated airspeed, m/s

v = corrected variometer reading, m/s ($v = C_v v_i$)

Λ = attitude, radians ($\Lambda = C_\Lambda \Lambda_{mm}$)

$$V^* = \frac{\sum_{t-n}^{t+n} V_i}{2n + 1}$$

$$\Lambda^* = \frac{\sum_{t-n}^{t+n} \Lambda}{2n + 1}$$

$\bar{V}$ = average airspeed throughout run = $\dfrac{\sum V_i}{\text{no. sets of data}}$

$$\frac{dv}{dt} = \frac{\dfrac{v_{+r+1} + v_{+r}}{2} - \dfrac{v_{-r-1} + v_{-r}}{2}}{\dfrac{t_{+r+1} + t_{+r}}{2} - \dfrac{t_{-r-1} + t_{-r}}{2}}$$

$$L = \frac{\alpha_o V_i}{g} \frac{dv}{dt}$$

$$M = \frac{2\alpha_o V_i}{V_o} (V_i - V^*)$$

$$N = V_i(\Lambda - \Lambda^*)$$

The averaging interval, 2n+1, varied from about 20 to 30 seconds (n is approximately equal to the number of seconds at camera speed of about 2 frames/sec.).

The interval, r, was such that the vertical acceleration was averaged over 1 to 2 seconds.

The programme was divided into two portions: an intermediate and a final. After the intermediate computations the following sets of data were printed out: time (in seconds from start of run where t=0), V_i (m/s), V^* (m/s), Λ^*_{mm}, L, M, N, H (meters), $\sum(t_i - t_{i-1})v + H_o$ (meters).

This latter figure, the integration of the variometer, was computed in order to check the conversion factor, C_v, which was originally determined by hand.

Correction factors, K_v and K_Λ, were inserted in the final program in case it was felt, after examining a dozen or so runs after the intermediate program, that C_v and C_Λ had been determined incorrectly. For example, C_v was originally estimated from hand computations to be 1.25. After examination of $\sum(t_i - t_{i-1})v + H_o$ it was decided that a more accurate figure would be 1.20, making K_v = 0.96.

The following sets of data were printed out after the final computations: time, v (m/s), W (m/s), U (m/s), θ_D, θ_V, MR, RH, t_D.

Example of reduced data

The following tables give an example of original data and reduced values printed out after the intermediate and final programs.

Imput:

Day	Flight	Run	C_v	C_{Λ}	C_D	n	r
18	3	3	+1.2	-.034	+1.06	30	1

time	H_{ft}	t_d	$(t_d - t_w)$	Vi_{mph}	v_i	Λ mm
0	4095	6.85	1.45	49.8	-.7	5.75
.7	4095	6.85	1.4	49.4	-.55	5.5
1.2	4095	6.85	1.35	49	-.5	5.5
1.7	4095	6.87	1.3	49	-.5	5.5
2.2	4095	6.87	1.35	49	-.5	5.5
3	4090	6.87	1.35	49	-.5	5.75
3.5	4090	6.9	1.35	48.6	-.5	5.75

. . . .

Cutput after intermediate program: $\bar{V}$ = 23.36

time	V	V*	Λ*	L	M	N	H	$(t_i - t_{i-1})v_i \pm H_o$
0	22.26	22.26	5.75	+0.03	+0.00	-0.00	1248	1248
.7	22.08	22.08	5.58	+0.04	+0.00	+0.06	1248	1247
1.2	21.90	22.01	5.55	+0.03	-0.03	+0.04	1248	1247
1.7	21.90	21.95	5.61	+0.01	-0.01	+0.08	1248	1247
2.2	21.90	21.84	5.72	+0.00	+0.01	+0.17	1248	1246
3.0	21.90	21.84	5.86	-0.00	+ 0.02	+0.08	1247	1246
3.5	21.72	21.90	5.92	-0.02	-0.04	+0.13	1247	1246
39.7	22.53	23.33	3.40	-0.08	-0.21	-0.46	1213	1218
40.2	23.24	23.33	3.41	-0.10	-0.02	-0.66	1213	1218
40.7	23.24	23.35	3.43	- 0.06	-0.03	-0.45	1212	1217
41.2	24.59	23.37	3.45	+0.07	+0.34	-0.04	1212	1216
41.7	25.21	23.39	3.46	+0.24	+0.52	+0.40	1212	1215
42.2	25.94	23.44	3.48	+0.35	+0.74	+1.08	1212	1215
43.0	24.94	23.48	3.48	+0.32	+0.42	+1.68	1213	1215
43.5	24.94	23.52	3.48	+0.19	+0.41	+1.26	1215	1215

. . . .

Imput before final program: K_v = 1.00 K_{Λ} = 1.00

. . . .

Output after final program:

time	v	W	U	θ_D	θ_V	MR	RH	t_D
0	-0.84	-0.01	+1.17	291.01	292.03	5.77	0.82	6.66
.7	-0.66	+0.13	+1.36	291.01	292.04	5.82	0.82	6.67
1.2	-0.60	+0.22	+1.56	291.02	292.05	5.86	0.83	6.67
1.7	-0.60	+0.14	+1.54	291.04	292.08	5.91	0.84	6.69
2.2	-0.60	+ 0.01	+1.50	291.04	292.07	5.87	0.83	6.69
3.0	-0.60	+0.10	+1.46	291.03	292.06	5.87	0.83	6.69
3.5	-0.60	+0.08	+1.63	291.06	292.09	5.88	0.83	6.72

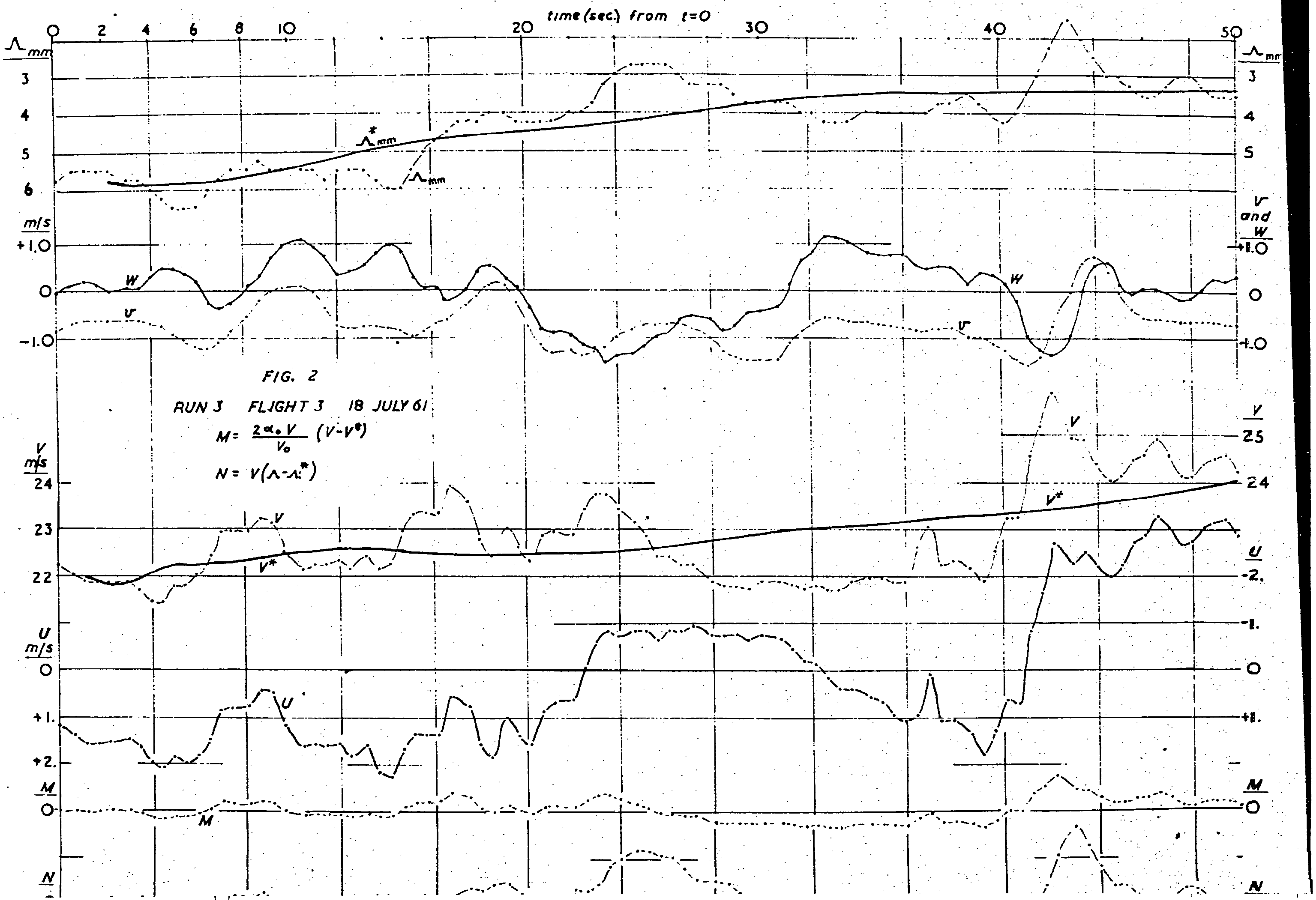


FIG. 2

RUN 3 FLIGHT 3 18 JULY 61

$$M = \frac{2\alpha_0 V}{V_0}(V - V^*)$$

$$N = V(\Lambda - \Lambda^*)$$

time	v	W	U	Θ_D	Θ_V	MR	RH	t_D
39.7	-1.08	+0.34	+1.26	291.12	292.33	6.89	0.95	7.11
40.2	-1.26	+0.17	+0.62	291.10	292.31	6.84	0.94	7.10
40.7	-1.44	-0.19	+0.70	291.09	292.30	6.84	0.94	7.10
41.2	-1.56	-0.95	-0.85	291.07	292.27	6.82	0.94	7.07
41.7	-1.38	-1.22	-1.68	291.08	292.28	6.83	0.94	7.08
42.2	-0.72	-1.33	-2.73	291.10	292.30	6.84	0.94	7.10
43.0	+0.00	-0.93	-2.28	291.12	292.33	6.85	0.94	7.12
43.5	+0.60	+0.02	-2.54	291.11	292.30	6.74	0.93	7.09

. . . .

Estimation of Accuracy

Fig. 2 shows the velocity data from the first half of Run 3, 18 July 1961, Flight 3 (part of which is given in the tables above). The accuracy of both the horizontal and vertical wind components is limited by the accuracy of the artificial horizon. This instrument was read to the nearest 0.25 mm; in terms of vertical velocity, an error of ± 0.25 mm corresponds to about $\pm$ 0.20 m/s. Another $\pm$ 0.2 m/s error may be introduced when attitude changes are comparatively great, due to a possible error in the conversion factor, C_{Λ}. An even greater error in the vertical velocity can occur when there are rapid changes of attitude.

An example is shown at t = 40 to 44 seconds on the diagram and is typical of what happens after an abrupt change in airspeed. Starting at t=39.2 there is a sharp increase in the airspeed. This is followed one second later by a "nose-up position" of the glider's attitude (Λ_{mm} decreases) - due either to the pilot inadvertently pulling back the stick or to the response of the aircraft to the horizontal gust. One second later, at t = 41.2, the glider starts to climb (or, more correctly, sink less rapidly). It appears, although we cannot be certain, that the vertical velocity changes between t=41 and t=46 are due to a change from kinetic to potential energy. Because there is a tendency to be slightly out of phase, the accuracy of the resultant wind speed, W, is decreased as the amplitude and frequency of the attitude change is increased.

The running means, Λ^* and V*, were averaged over approximately 20 seconds except at the beginning and end of the run when, for example, the mean at the second point was the average of only three points. This is satisfactory when the attitude and airspeed changes at the beginning and end are small, but additional error is introduced when they are large. In these cases Λ^* and V* were extended from about ten seconds to give a smooth slope, and values of "M" and "N" were determined by hand and used to adjust the machine-computed values of W and U.

The error introduced in W due to an error of ± 1.0 mph is only about ± 0.1 m/s and is comparatively negligible.

It is not possible to state the exact accuracy of the vertical speed, W. In general an accuracy of ± 0.4 m/s was assumed except immediately after rapid and large changes of airspeed and/or attitude. On a number of runs, where the changes in W and U (or V) are less than about 2.0 m/s, it is probably safe to assume the accuracy is at least as great as ± 0.3 m/s. No attempt has been made, and perhaps should not be made, to study the small scale fluctuations.

No attempt will be made to ascertain the accuracy of the absolute value of U. It should be safe to assume that the changes in the horizontal wind over comparatively short periods are accurate to about ±20% (but never greater than ± 0.4 m/s). When determining net inflow or outflow into the thermal conclusions were not drawn unless the graph of both U and V indicated a significant net flow.

On some of the graphs, mostly those where there are comparatively large attitude changes, both W and v, and U and V, were plotted.

Part III THE DATA

18 July 1961

Four flights were made on this day. Pertinent information, including ground and flight observations are given below. Times are British Summer Time (GMT + 1 hour).

Site: Lasham, Hampshire

Forecast: 0 - 3/8 str. cu increasing to 5/8 cu, base 900-1500 m., tops 2000 - 2400 m., showers unlikely

0730 cloud nil, wind slight

0900 small cu forming, base 7 - 900 m., surface wind N 2-3 knots, at cloud base 10 knots NW

0920 cu increasing very rapidly, cover increased from 1/8 to 3/8 in 10 minutes

0940 cu increased to 6/8 cover, base about 800 m; wind at base NNW 10 knots

1030 cu cover decreased to 5/8, base about 900 m., tops about 1200 m.

1104 glider takes off; visibility 6-8 miles, surface wind N 5-8 kts., cloud base 975 m., cover 5/8, tops of smaller cu observed at 1100m.

1136 glider lands

1145 glider takes off for Flight 2; good lift, and down, encountered on tow; from ground cu seen to be growing quite rapidly to about 1500m.

1218 glider lands

1230 cu increasing in size and giving 6/8 cover

1240 glider takes off for Flight 3; cloud base about 1325 m., cover increasing to 7/8, wind at ground 1-2 kts.

1250 some cu flattening out into strato-cu, some forming well and going to 1600-1800 m.

1300 nearly solid spread-out of cu above glider

1325 glider lands

1330-1500 strato-cu about 13-1400 m., nearly complete cover, lift marginal

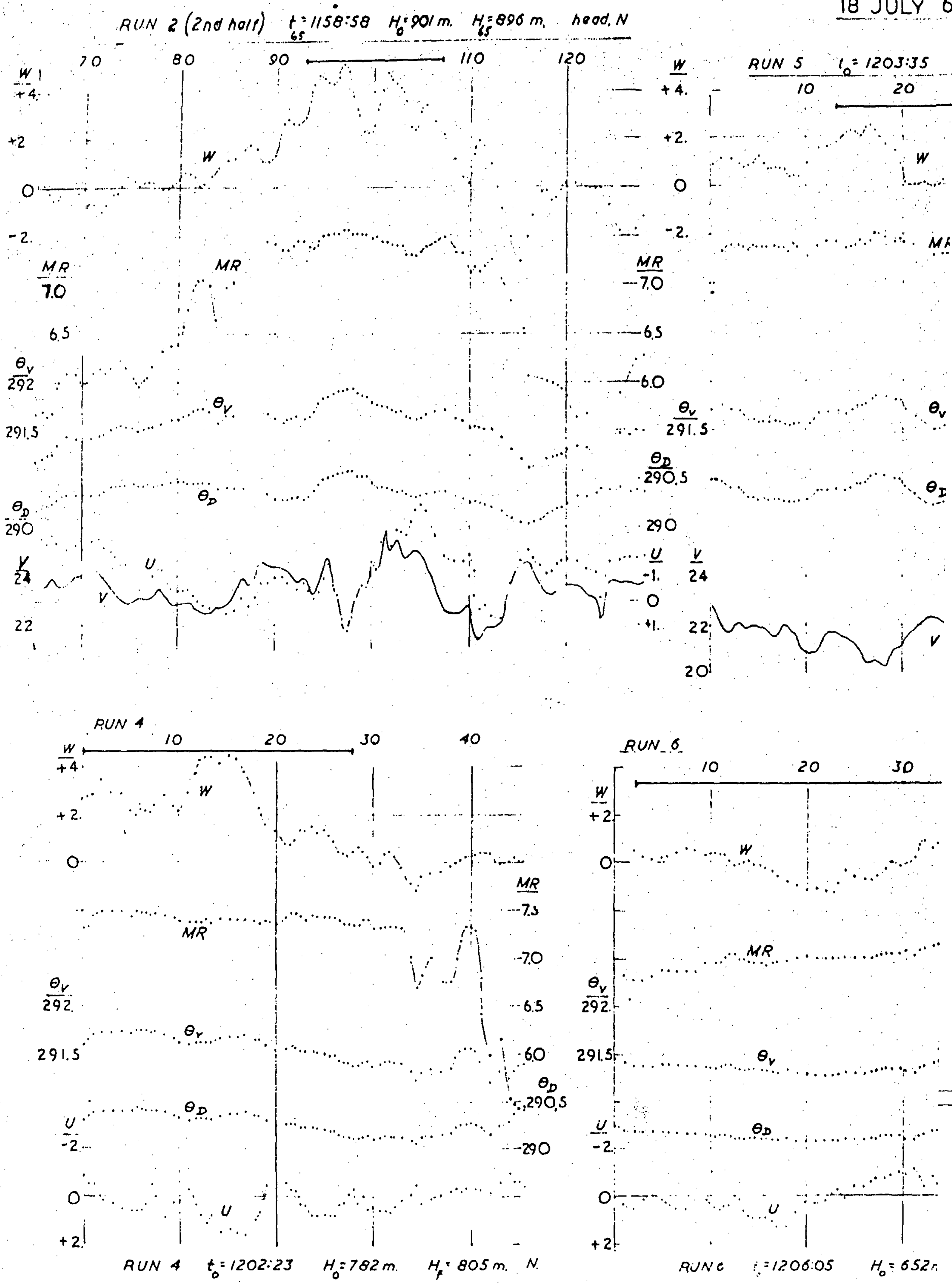
1530 7/8 overcast, some cu underneath, surface wind N 8-10 knots

1600 glider takes off for Flight 4; cover decreased to about 5/8; dark and overcast to NW, ill-defined base about 1400 m., visibility 3-5 miles. From ground: one or two larger cu develope to about 2000 m. but flatten out.

1644 glider lands

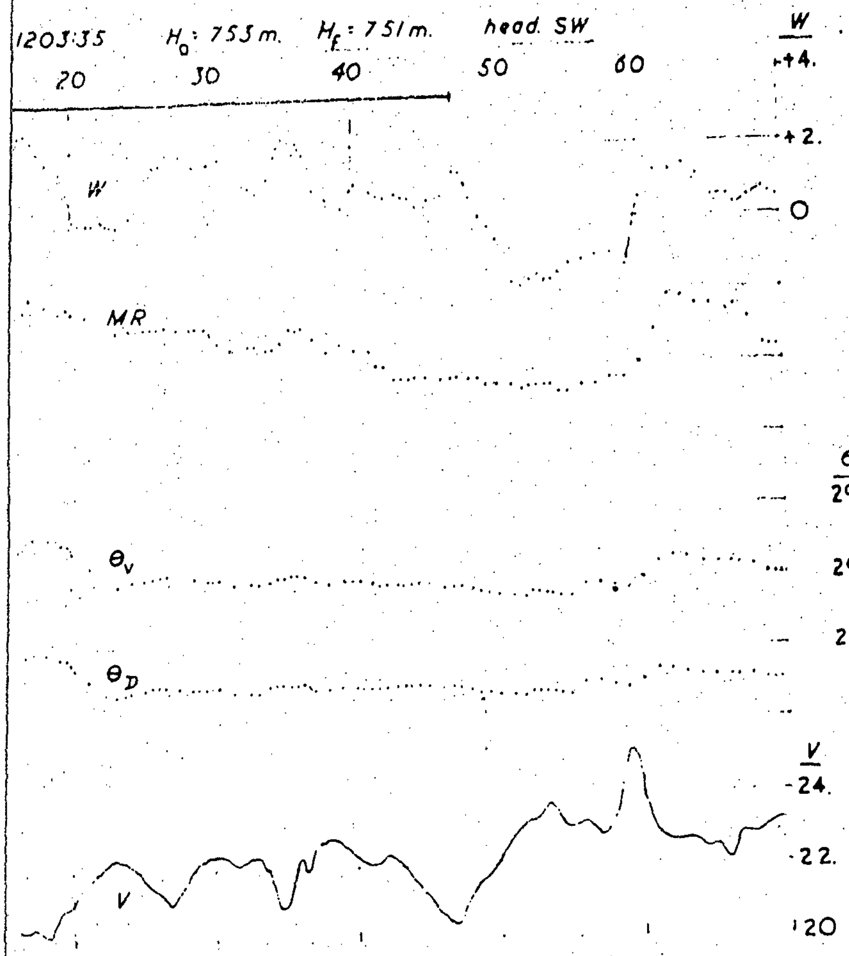
1700- cloud broke up (from about 1600) and cleared during late afternoon and evening

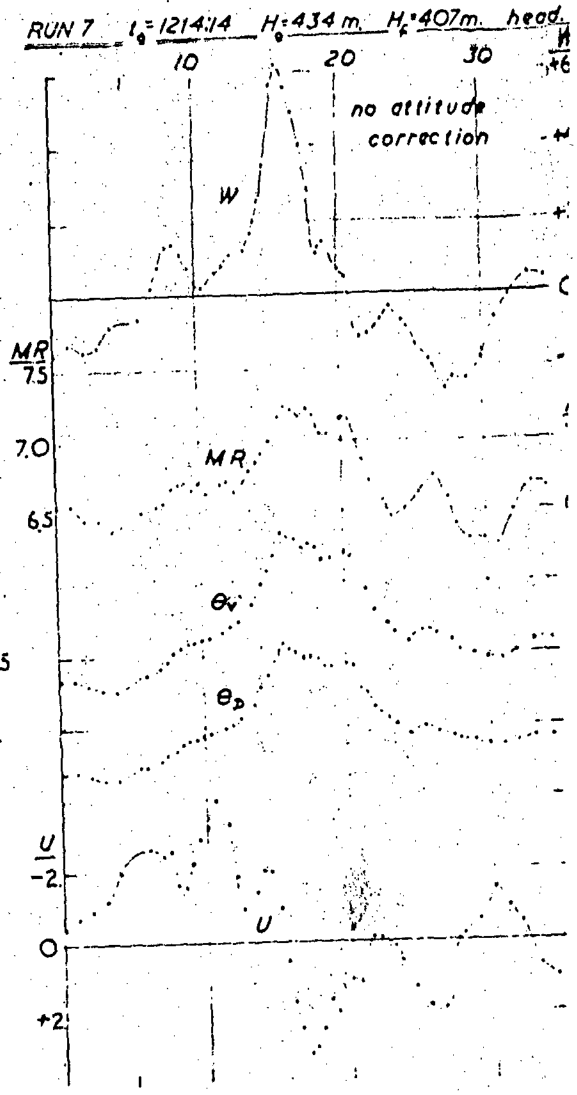
18 JULY 6

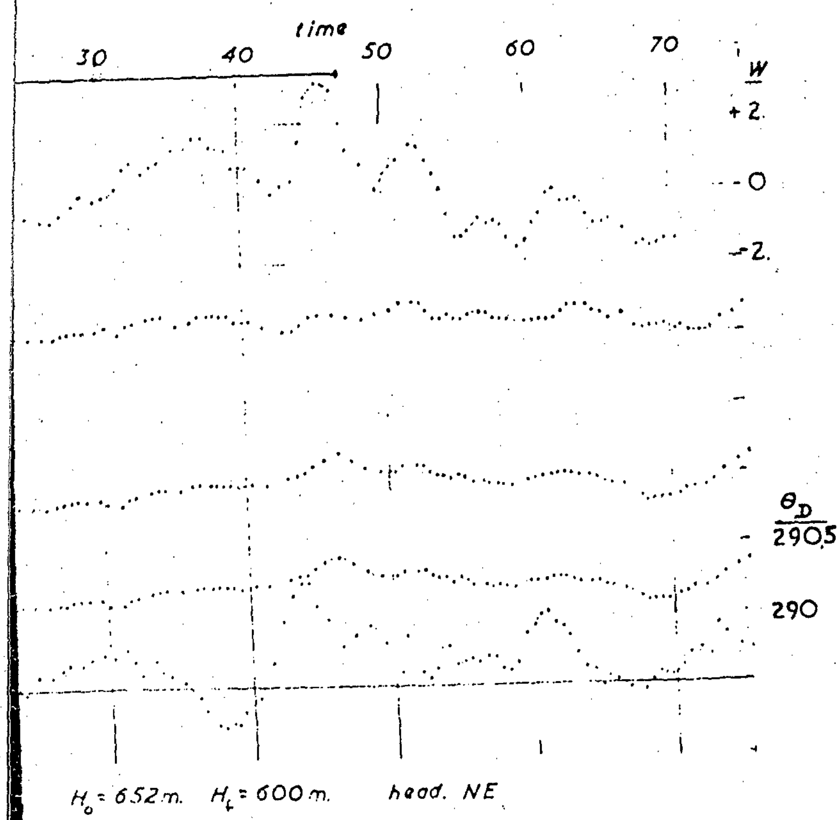


RUN 2 (2nd half) t_{65} = 1158:58 H_0 = 901 m. H_{65} = 896 m. head. N
70 80 90 110 120
W +4 +2 0 -2
MR 7.0 6.5 6.0
θ_V 292 291.5
θ_D 290.5 290
U -1 0 +1
V 24 22 20
RUN 5 t_0 = 1203:35
10 20
RUN 4
10 20 30 40
MR 7.5 7.0 6.5 6.0
θ_V 292 291.5
θ_D 290.5 290
U -2 0 +2
RUN 4 t_0 = 1202:23 H_0 = 782 m. H_f = 805 m. N.
RUN 6
10 20 30
W +2 0
MR
θ_V 292 291.5
θ_D
U -2 0 +2
RUN 6 t_0 = 1206:05 H_0 = 652 m

JULY 61 FLIGHT II







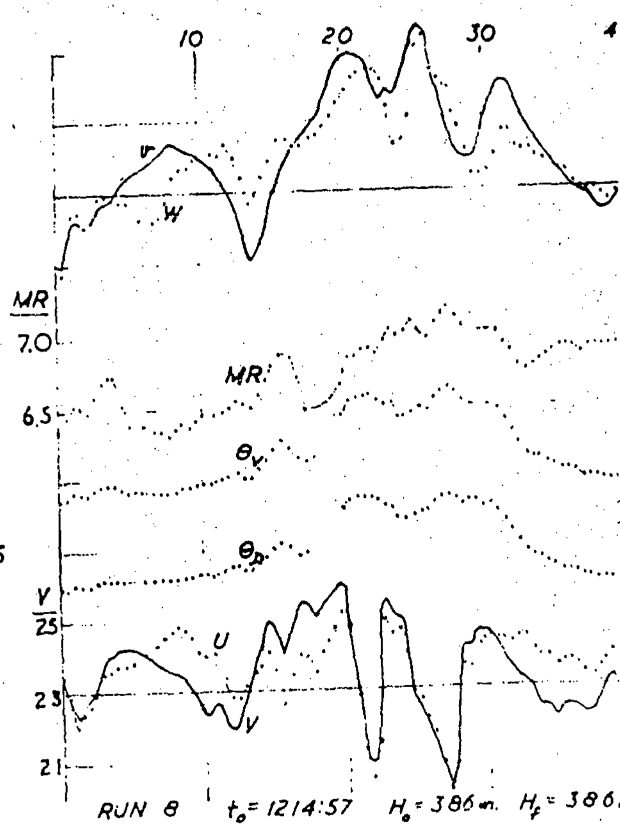


Fig. 3 18 July '61 Flight 2

The diagram opposite shows data obtained during six traverses through a thermal. Runs 2, 4, 5, and 6 were made at heights from 901 m to 600 m through one thermal. Runs 7 and 8 were made through a different thermal at heights from 434 to 386 m.

The scale used is the same for all diagrams:

W, vertical wind speed	1 cm = 2.0 m/s
MR, mixing ratio	1 cm = 0.5 gr/km
θ_V, virtual potential temperature	1 cm = o.5° A
θ_D, dry bulb potential temperature	1 cm = 0.5° A
U, horizontal wind speed (positive in direction of glider)	1 cm = 2.0 m/s

In some cases V, airspeed of glider, has been plotted. In Run 8 the vertical speed of the glider, v, has been plotted, taking the normal sinking speed into account; i.e., if there were no corrections for attitude, airspeed or vertical acceleration then the two curves, W and v, would coincide.

All are plotted vs. time (t = 0 at start of run) and 1 cm = 5 seconds or approximately 120 meters. The altimeter was set at 1013 mb which gave H = 156 m. at airfield elevation.

Run 2 was made about 150-200 m. below cloud base under a small cumulus that had just recently formed. The data obtained is typical of what one would expect when traversing a moderately strong thermal. The horizontal extent of the cloud above is shown from 93 to 107 seconds, i.e. a width of about 340 m.

Run 3 is not shown; the pass was not made through the centre of the thermal.

Run 4 began, or rather the camera was turned on, when passing under the southern edge of the cu above. The vertical velocities are still comparatively high, about 4 m/s; the horizontal dimensions of the cloud have increased. (It should be noted that a mark is made when the glider is directly under the edge of the cloud. As the distance between the cloud base and the glider increases the lift that is encountered is displaced upwind. For example, when heading in a northerly direction the cloud above would be shown, on the diagram, to the left of the area of lift. The wind at cloud base was NNW 10 knots.)

There is a region of comparatively dry air (Run 4) on the northerly edge of the thermal; there is a decrease of 1.3 gr/km in about 36 meters.

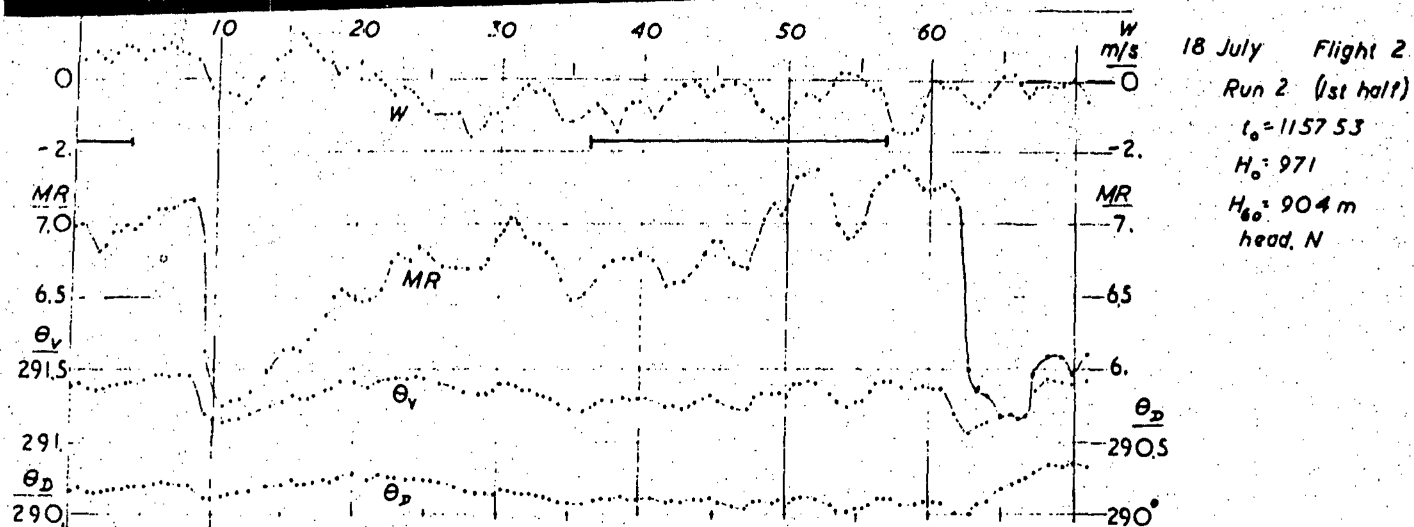
A minimum value of 5.4 gr/km is reached, compared with an average value of 7.4 gr/km in the thermal. If the run had been continued it is probable that the mixing ratio would have increased fairly rapidly to 6.5 or 7.0 gr/km. There are a considerable number of cases where the thermal is surrounded by a comparatively narrow belt of dry air. It can be argued that this dry air must have come from above cloud base. This will be discussed later.

Run 5, made about 350 m. below base, shows a considerable decrease in the vertical velocity. The glider is now probably well below the main part of the thermal.

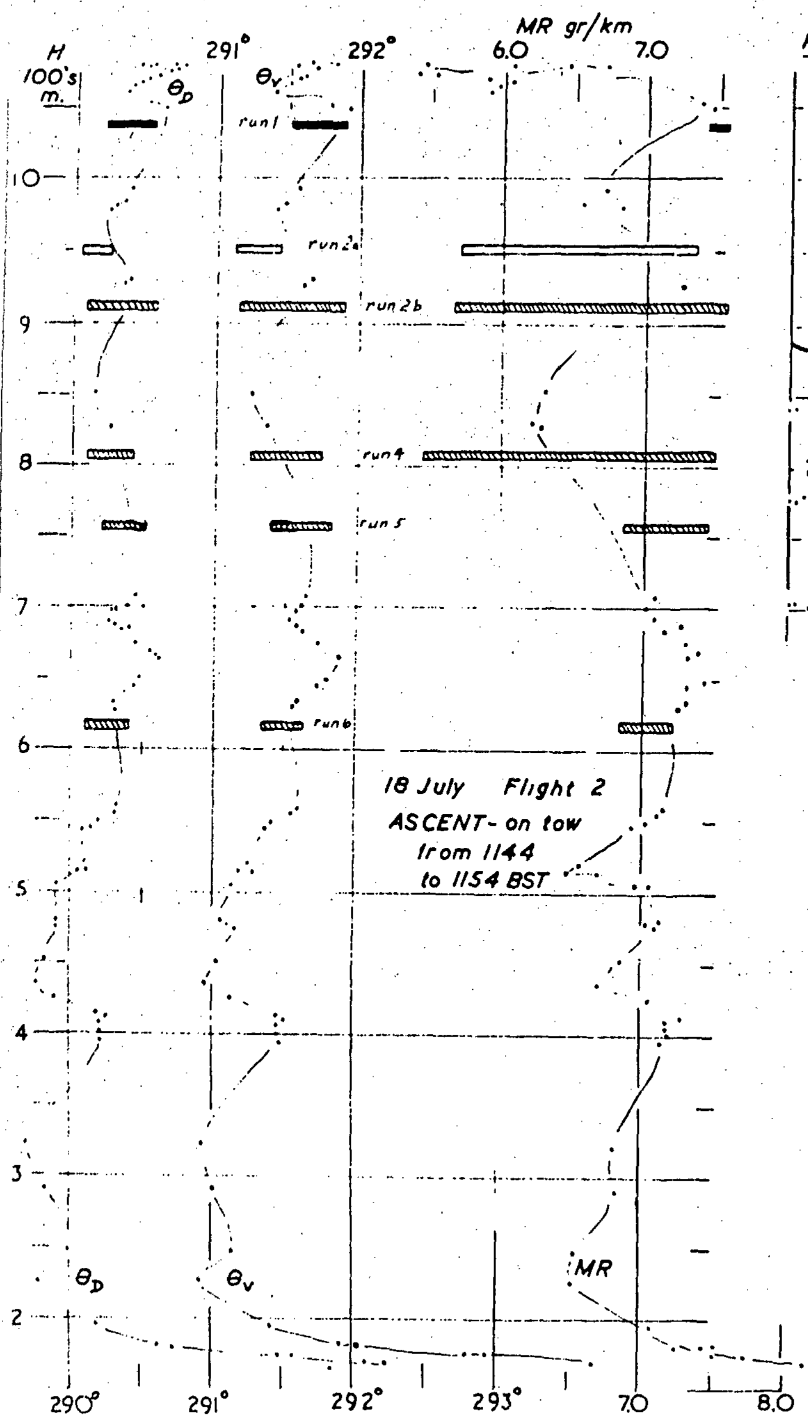
When Run 6 was made it was noted that the edges of the cu above were becoming ragged. There is a definite indication of inflow from the horizontal wind speed (positive followed by negative U midway through the region of lift). Compare MR, Θ_V, and Θ_D with curves obtained in Run 2.

Run 7 was made at a height of about 270 m. above the ground. A glider was spiraling less than 50 m. above and this glider was used to mark the thermal. There is no correction to the velocities for attitude. (The artificial horizon had been turned off.) The thermal is considerably narrower and the temperature excess greater than that encountered in the previous thermal 500 m. higher. There is an indication of outflow but one should perhaps not put too much emphasis on this since U is not corrected for attitude.

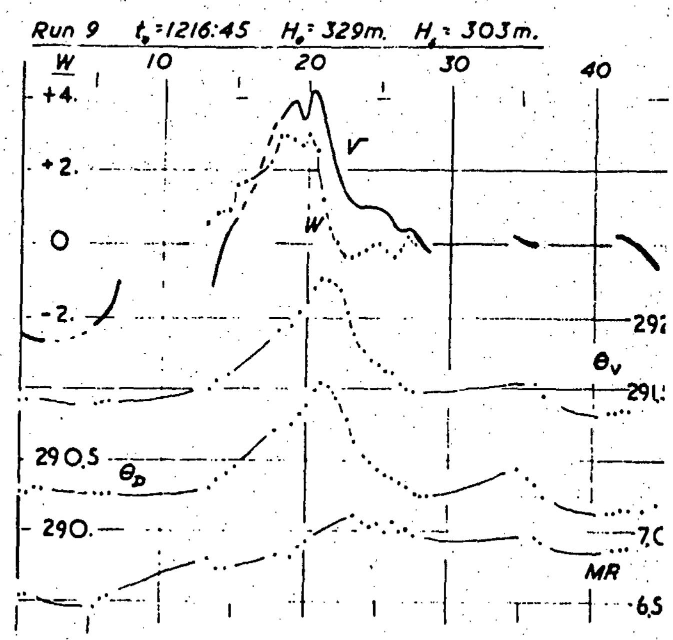
Run 8 is a second pass made through the same thermal about 30 m. lower; or roughly 130 m. lower, relative to the thermal cap, if one assumes isolated thermal theory. The artificial horizon had just been turned on; because of this both v and V have been plotted.



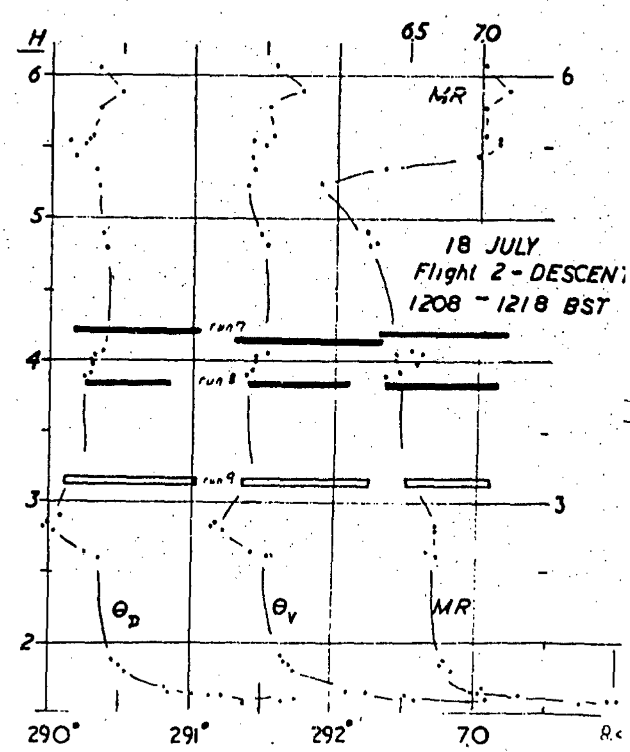
18 July Flight 2
Run 2 (1st half)
t_o = 1157 53
H_o: 971
H_{60}: 904 m
head. N
W m/s
MR
θ_V
θ_D



H 100's m.
MR gr/km
run 1
run 2a
run 2b
run 4
run 5
run 6
18 July Flight 2
ASCENT - on tow
from 1144
to 1154 BST
θ_D
θ_V
MR



Run 9 t_o = 1216:45 H_o: 329m. H_A = 303m.
W
V
θ_V
θ_D
MR



H
MR
18 JULY
Flight 2 - DESCENT
1208 - 1218 BST
run 7
run 8
run 9
θ_D
θ_V
MR

Figure 4

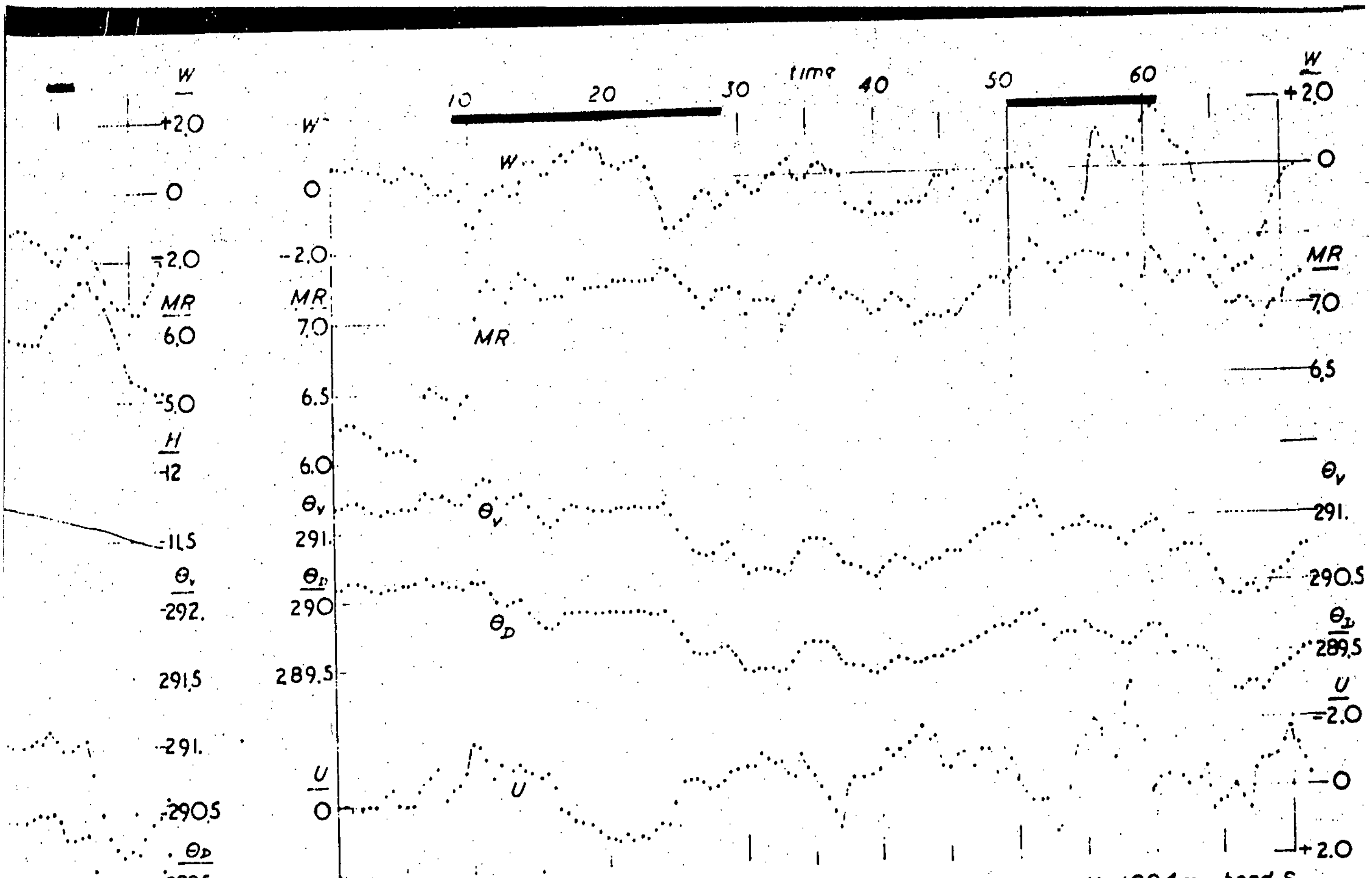
The soundings made, during Flight 2, July 18, while on tow and during descent are shown opposite. θ_D, θ_V; and MR are plotted against pressure height, H, in meters. The height of the airfield is 157 m. with the altimeter set at 1013 mb. (True height of airfield is 170 m. ASL). The range of values obtained for θ_D, θ_V, and MR during the runs are plotted at their mean heights. Also shown in the figure are values obtained during the first part of Run 2 and during Run 9.

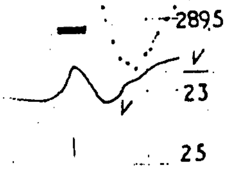
Sounding, ascent: The first readings were made at a height of about 5 m. above the ground. There is a sharp decrease in the potential temperatures and mixing ratio in the lowest levels. It should be pointed out that after the glider has reached a height of 30 - 50 m. it is no longer over the airfield (grass, with dark concrete runways) so that one must bear in mind that temperatures recorded at 160 m. are over a different region than those taken at, say, 250 m. Nevertheless, from all the soundings made it is difficult to discern any appreciable super-adiabatic lapse rate except in the lower few dozen meters.

The glider released from the tow plane in clear air at 1080 m., just above the cloud base. The bases were ill-defined and varied roughly 30 - 50 meters. The first run (range of values only shown) was made through the base of a small cumulus at a height of 1040 - 1035 m.

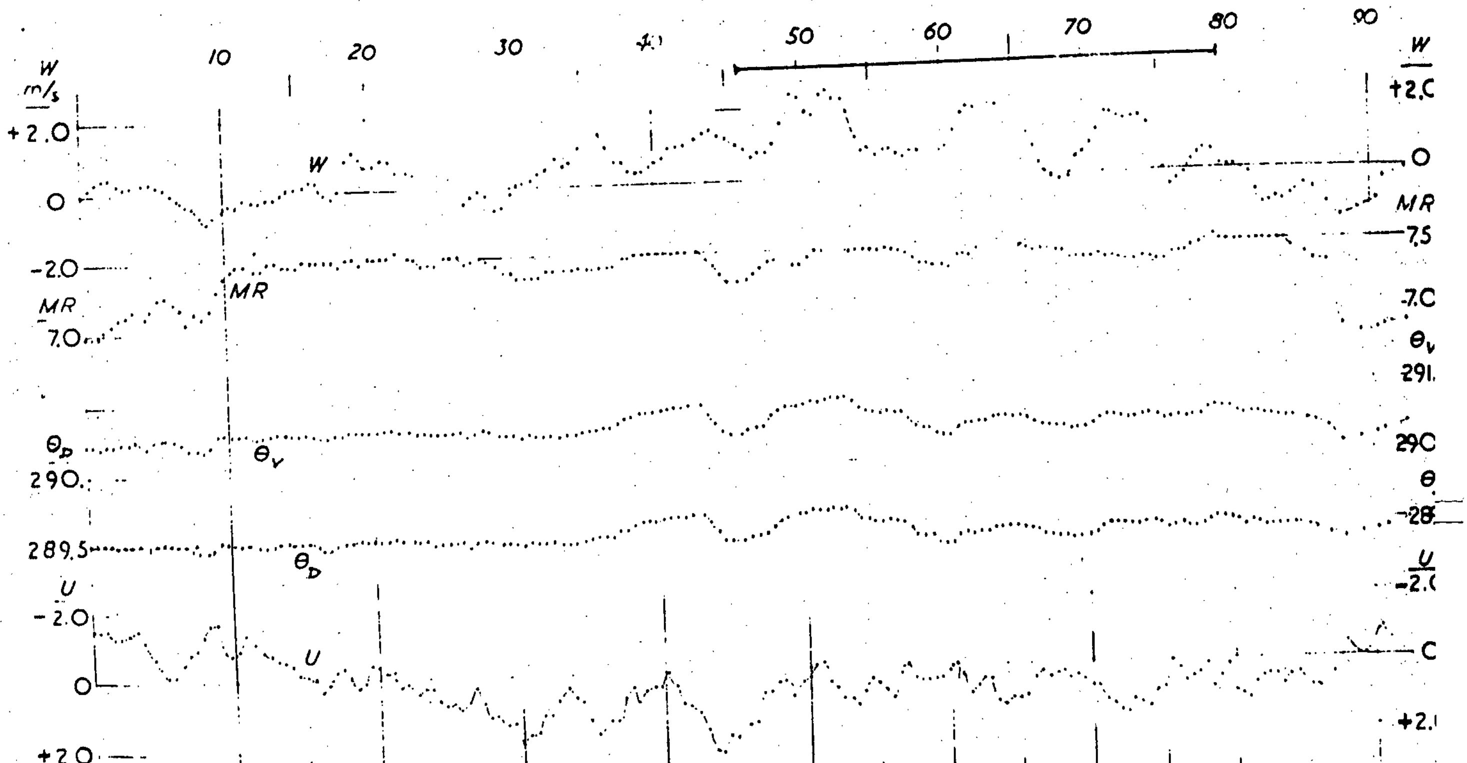
The first half of Run 2 is shown at the top of the figure. A mark was made at 4 seconds to indicate the glider was passing from under the edge of one cloud and at 36 and 57 seconds to indicate flying under another. Again we have the very steep gradient of mixing ratio. The air is descending slightly under the cu and it is negatively buoyant. A note was made that the cu appeared to be in the dissapating stage.

The thermal encountered during Run 9 was at a height of about 160 m. above the ground. The data is not continuous because the camera was operated by hand, and reduction of W was by hand. This is the greatest temperature excess that was encountered.





18 July Flight I Run 2 t_o = 1122:01 H_o = 1081m. H_f = 1004m. head. S



18 July Flight I Run 3 t_o = 1126:19 H_o = 792 m. H_f = 762 m. head. N

Fig. 5. 18 July Flight 1

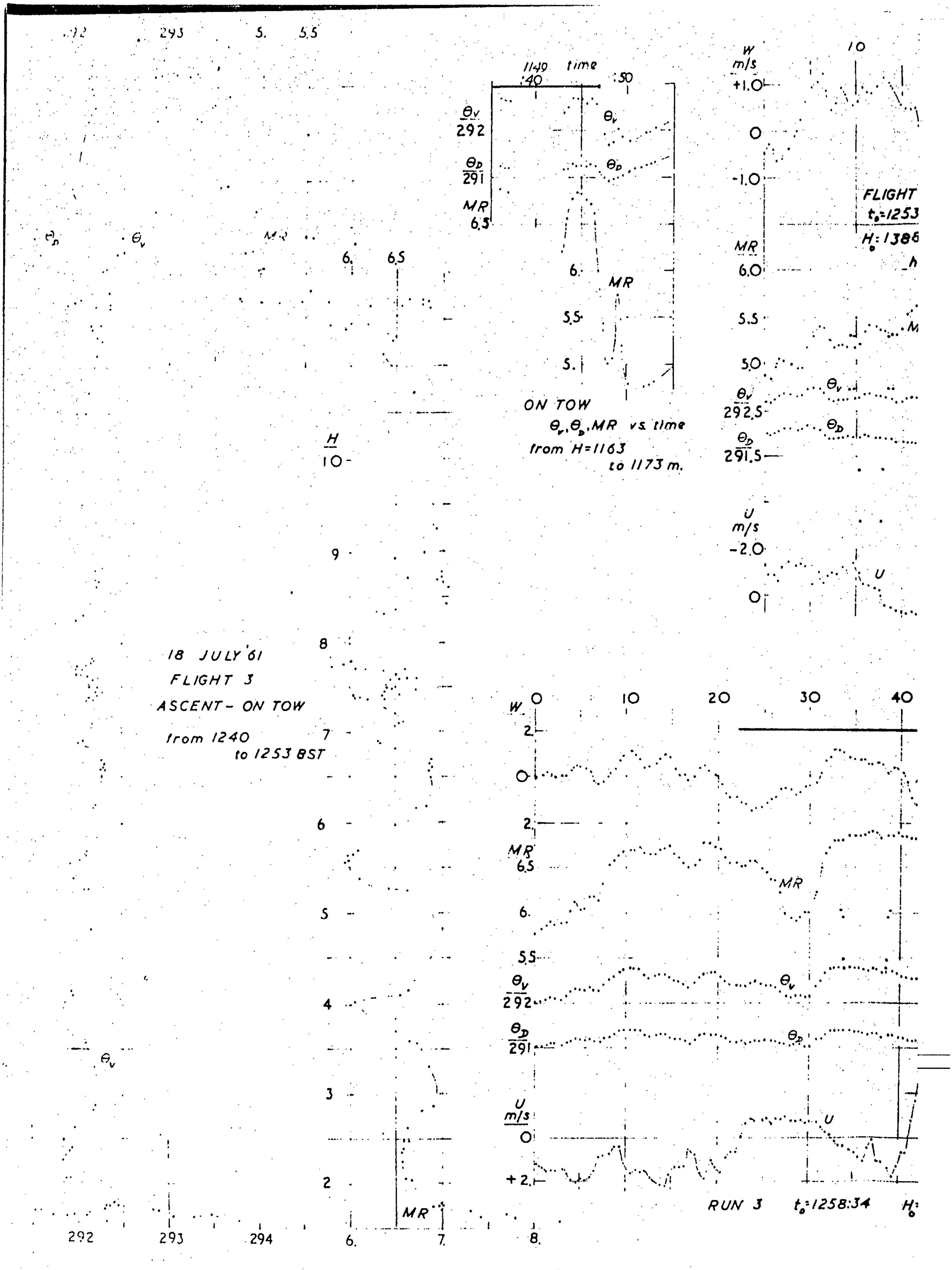
This flight was made just prior to the one previously described. The tow was continued above cloud base which was about 975 m. The tops of the smaller cu extended to approximately 1100 m., a few had risen to roughly 1200 m. It was quite stable above the base (slight inversion at 1100 m.) and the air was dry.

Run 1 was made through the top of a cumulus. One must not be too ready to accept temperatures taken inside cloud, and for 2 or 3 seconds after emerging, but those which have been recorded appear to be reasonable. The tops of the cu are buoyant only with respect to their immediate surroundings. (Note that mixing ratio scale has been doubled so that 1 cm = 1.0gm/km).

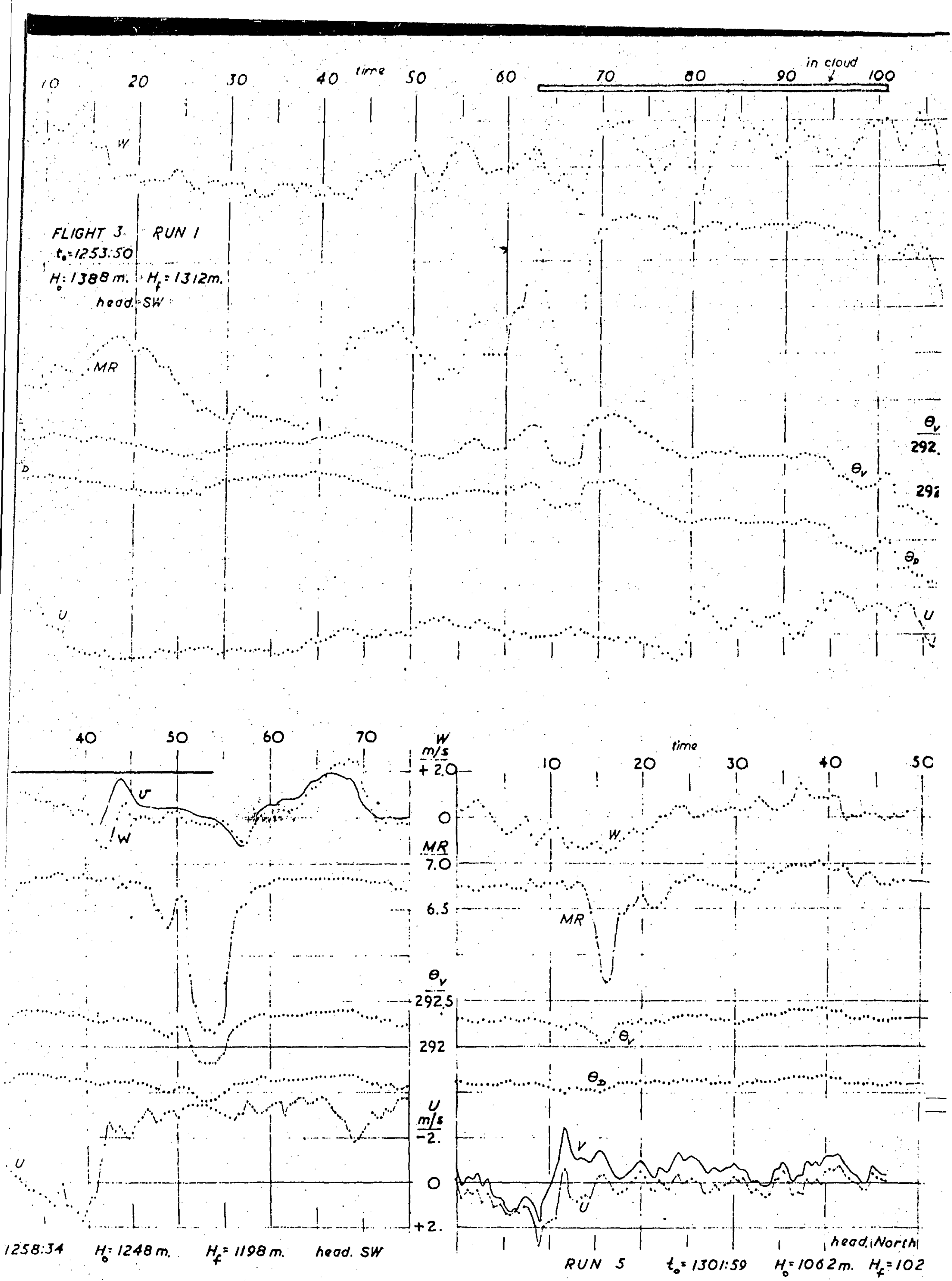
Run 2 was made through two cumulus approximately 50 m. above their bases. There is a steep gradient of the mixing ratio only when entering the first cumulus. A moderately strong downdraught and a comparatively large temperature gradient were recorded after emerging from the second cloud.

On Run 3 there appears to be three separate regions of lift under the cumulus. The situation is not clear cut.

On the descent a comparatively wide area of sink (4 m/s) was encountered at about 500 m.



18 JULY '61
FLIGHT 3
ASCENT - ON TOW
from 1240
to 1253 BST
ON TOW
θ_v, θ_D, MR vs time
from H=1163
to 1173 m.
1140 time
:40
:50
θ_v
θ_D
MR
H
W
m/s
U
m/s
FLIGHT
t_o=1253
H_o: 138
RUN 3
t_o:1258:34
292
293
294
6.
6.5
7.
8.



FLIGHT 3 RUN 1
t_o=1253:50
H_o:1388 m. H_f=1312m.
head. SW
time
in cloud
10 20 30 40 50 60 70 80 90 100
W
MR
θ_v
292.
θ_D
U
40 50 60 70
U
W
W m/s
+2.0
0
MR
7.0
6.5
θ_v
292.5
292
U m/s
-2.
0
+2.
time
10 20 30 40 50
V
U
1258:34 H_o= 1248 m. H_f= 1198 m. head. SW
head. North
RUN 5 t_o= 1301:59 H_o= 1062 m. H_f= 102

Fig. 6. 18th July Flight 3

Flight 3 was made about noon G.M.T. The lapse rate is neutral except for the unstable ground layer and the stable layer near cloud base. Cloud cover had increased to 7/8, due to spreading out of cu. While on tow it was noted that base was roughly 1340 m; however, on Run 1 the glider was in cloud at about 1315 m. At 1170 m the glider was towed under a cu. Values of θ_V, θ_D and MR are plotted vs. time (or horizontal distance, 1 cm $\approx$ 140 m) for this portion. There is a rapid decrease in mixing ratio (about 1.0 gr/km in 30 metres) when the glider passes under the edge of the cloud above.

Run 1 was made above cloud base. From 4 to 18 seconds there is a region of lift. (Vertical velocity scale has been altered so that 1.0 cm = 1.0 m/s. There was little change in attitude throughout this run so that greater accuracy was achieved.) There is an indication of temperature excess and increased moisture content (though the latter is slightly out of phase). The horizontal velocities indicate a region of outflow. This may be a case of the glider passing through the top of a thermal in which, because of dryer air mixing in the thermal cap, the moisture content is not high enough to form cloud. Several times the writer has encountered weak lift in clear air above cloud base. The glider's position can be maintained for about a minute as condensation slowly takes place around the aircraft. Lift then increases and the glider can rise in the newly formed cu.

In the latter part of the Run cloud was entered at 1335 m.

Run 3 is the same as that given in the previous section on data reduction. During the run a note was made that the cloud above was in the dissipating stage. The data obtained corroborates the observation. Insignificant lift was encountered and there is a definite indication of inflow. The cloud above was the same as that entered during the latter part of Run 1. (The 2nd run to the NE is not shown; it was started just after the edge of the cu had been passed.) When the glider emerged from under the NW edge a similar drop in mixing ratio was encountered.

At the time of Run 5 there was a nearby complete spread out of cumulus above. We still encounter the comparatively narrow bands, or pockets, of dry air. It is believed that these pockets have descended from the relatively dry region above cloud base. They appear to be more prevalent during the latter stage of a thermal's rise, i.e. well after cloud has formed. The steep gradient and narrow width indicate that there has been comparatively little mixing between the dry descending air and the moist ascending air. These pockets extend at least 300 m below cloud base.

Run 5 continued longer than shown but the camera unfortunately ran out of film. During the latter part of the run (not shown) the glider flew under "a fairly dark base" where a wide area of lift was encountered.

Temperatures were noted on the ascent. The dry bulb potential varied from 291.0 to 291.3°A and MR from 6.0 to 7.0 gr/km between 250 and 500 metres.

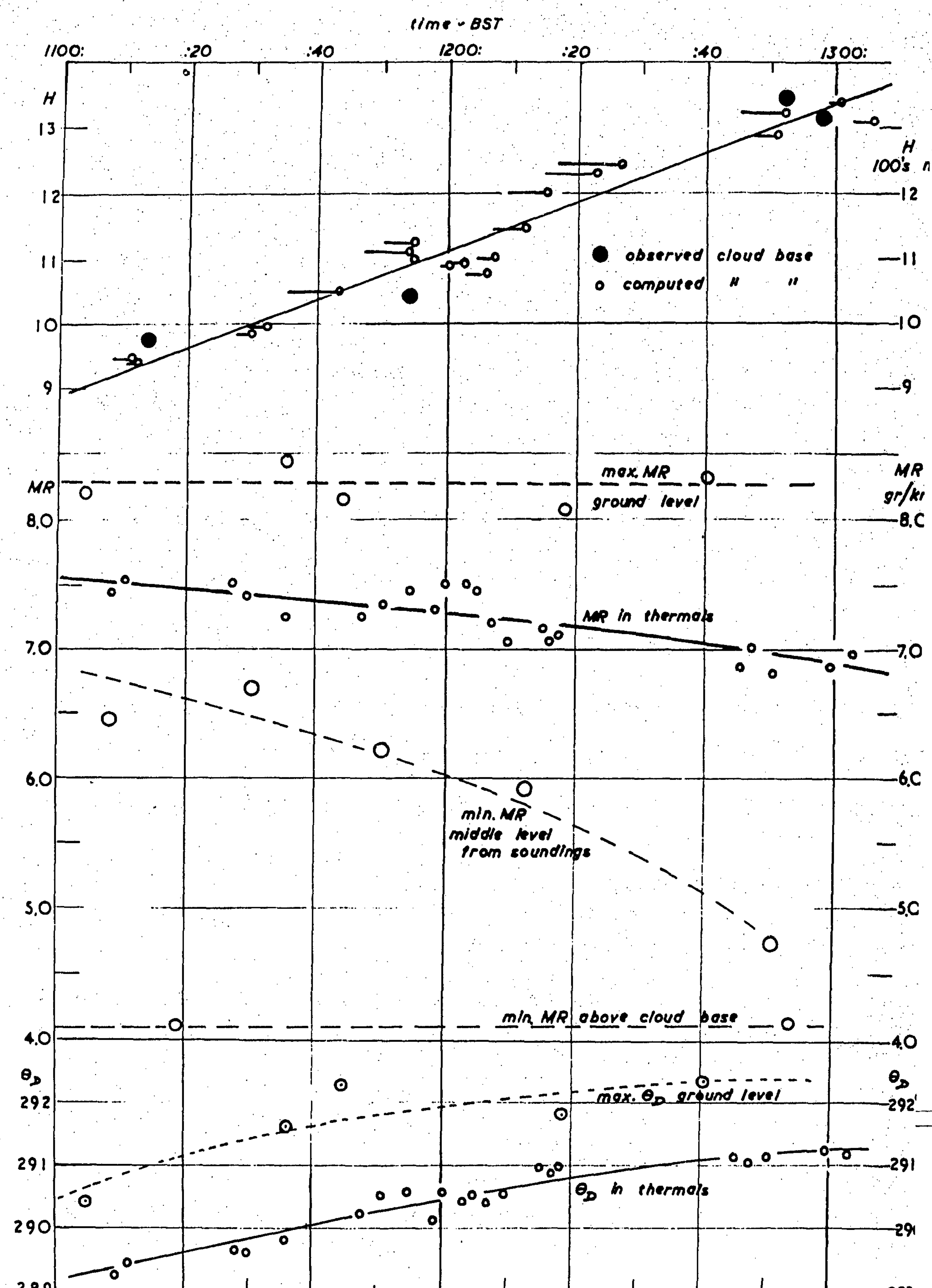

time - BST
1100:
:20
:40
1200:
:20
:40
1300:
H
H
100's m
13
12
11
10
9
observed cloud base
computed " "
MR
MR
gr/kg
8.0
7.0
6.0
5.0
4.0
max. MR
ground level
MR in thermals
min. MR
middle level
from soundings
min. MR above cloud base
θ_D
θ_D
292
291
290
289
max. θ_D ground level
θ_D in thermals

Fig. 7

Cloud base, MR, and θ_D vs time

It is of interest to summarise the temperature and mixing ratio obtained during the first three flights on July 18, from 1100 hrs. to about 1300 hrs. BST. During these two hours the cloud cover increased from 5/8 to 7/8, and the cloud depth from 200 metres to very roughly 500 m; at the latter time, however, the majority of the cover was due to "spread out" of strato-cu.

The cloud base was observed at four times; as stated previously, it was ill-defined. Dry bulb potential temperatures and mixing ratios that were encountered when traversing thermals, either on runs or during soundings, have been used to compute cloud base (assuming parcel theory). These computed values have been displaced in time to allow for the thermal to reach condensation level. A rate of rise of 100 metres/ minute was assumed. A linear line has been drawn through the points giving a rise of cloud base of about 200 m per hour.

The maximum mixing ratio observed at ground level is roughly constant with time; there is an increase and then leveling off of dry bulb potential temperature. All measurements at "ground level" were taken when the glider had reached an airspeed of about 20 m/s and the instrument a height of roughly 2 metres. The maximum values were always recorded below about 15 metres over the airfield. (During take-off and landing the glider samples only a small portion of air; the maximum values recorded, therefore, are not necessarily the maximum values over the airfield at that time.)

The mixing ratio and θ_D values used to compute cloud base are plotted. There is a decrease of about 0.15 gr/km per hour in the mixing ratio. The minimum MR values obtained during the soundings, which are also plotted, show a greater decrease with time. Only two points of minimum MR above cloud base are shown. It was only on two occasions that the glider was towed to sufficient height above the base.

The decrease of MR in the middle levels suggests that the relatively dry air above cloud base has descended adjacent to the rising thermals and that this dryer air was eventually mixed into latter thermals.

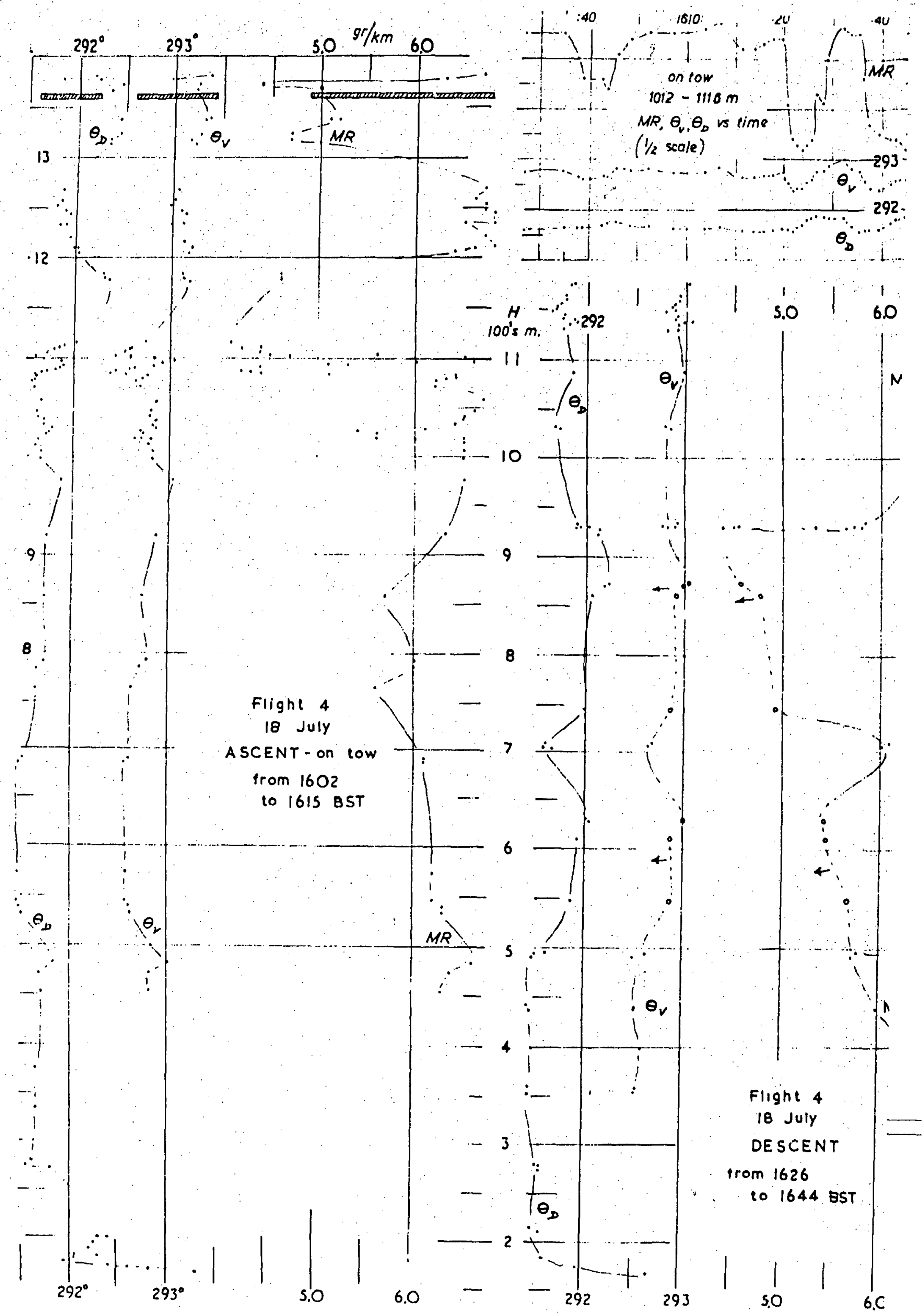

292°
293°
gr/km
5.0
6.0
θD
θV
MR
on tow
1012 - 1116 m
MR, θV, θD vs time
(1/2 scale)
:40
1610
20
40
293
292
H
100's m.
13
12
11
10
9
8
7
6
5
4
3
2
Flight 4
18 July
ASCENT - on tow
from 1602
to 1615 BST
Flight 4
18 July
DESCENT
from 1626
to 1644 BST

Fig. 8. 18 July 1961 Flight 4

Flight 4 was made later in the afternoon, from 1602 to 1644, primarily to make a sounding.

Visibility was poor, about 4 miles, and cloud cover began to decrease from 7/8 to about 5/8.

From 1000 m to 1100 m a pass, while still on tow, was made under a cu and the values obtained are plotted on the diagram (1 cm = 1.0 gr/km; 1 cm = 1.0°A; 1 cm = 10 seconds). Cloud base, which was ill-defined, was observed at about 1400 m. The range of values obtained during the first run after release are plotted on the ascent sounding at 1360 m.

There were areas of weak lift, and soaring was possible. The values at 1150 m on the descent sounding were obtained while spiraling in a thermal. A dry bulb potential temperature of 291.8°A and mixing ratio of 6.7 gr/km give a computed cloud base of 1450 m.

In the lower levels Θ_V and MR are not plotted because the instrument measuring wet bulb depression was off-scale (greater than 5°C). The circles at about 800 and 600 metres denote the maximum possible values of Θ_V and MR, i.e. (t_D-t_W) was taken equal to 5.0°C.

19 July 1961

Three flights were made on this day. Ground and flight observations are given below.

After an overnight rain there was stratus covering most of the sky at 0730. During the next hour there was some clearing and cu began to form at about 800 m. Cu increased rapidly and at 0900 there was 6/8 cover, with some alto cu above it. Wind E to NE 5 kts.

Forecast: 5/8 strato-cu at 900 m rising at 1500 m. Strong inversion at 650 mb and above that unstable air up to tropopause. Showers predicted later. Winds 10 - 12 knots.

....

1030 low strato cu gradually burnt off leaving 4/8 cu.

1130 wind NE 5-10 kts; small cu now well formed — each separate, remaining shallow.

1218 glider takes off for Flight 1; cloud base about 1150 m, wind NE 10 kts.

1259 glider lands

1315 glider takes off for Flight 2; 4/8 small scattered cu, base 1200.

1400 cu thickening and becoming more spread out.

1455 glider lands.

1500-1700 cu gradually decreasing until 1700 when only one broken line of shallow cu deserved to east.

1655 glider takes off for Flight 3. Wind at cloud base NNE 10 kts., cloud base 1400.

1745 glider lands.

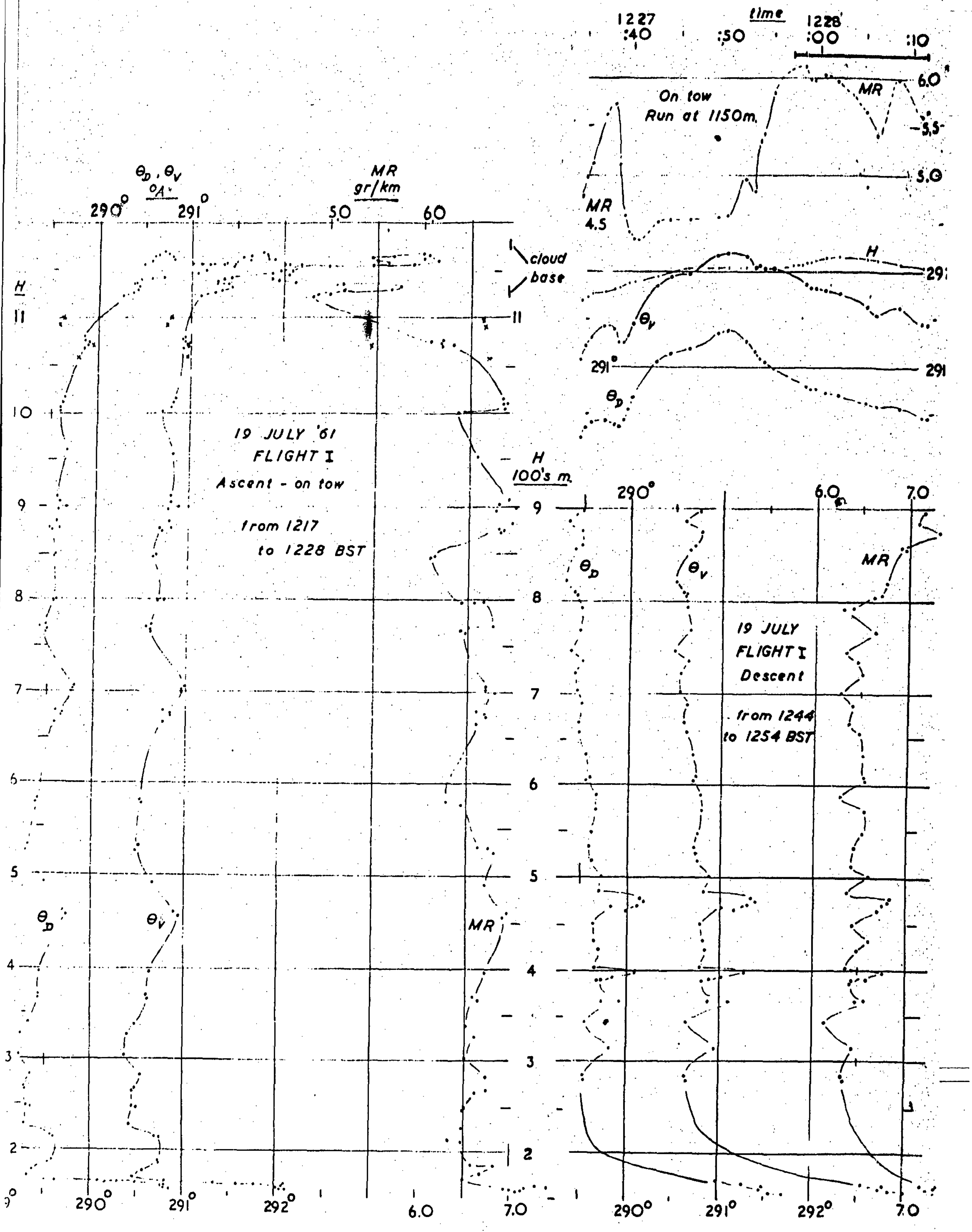
C 11

Fig. 9. 19 July Flight 1.

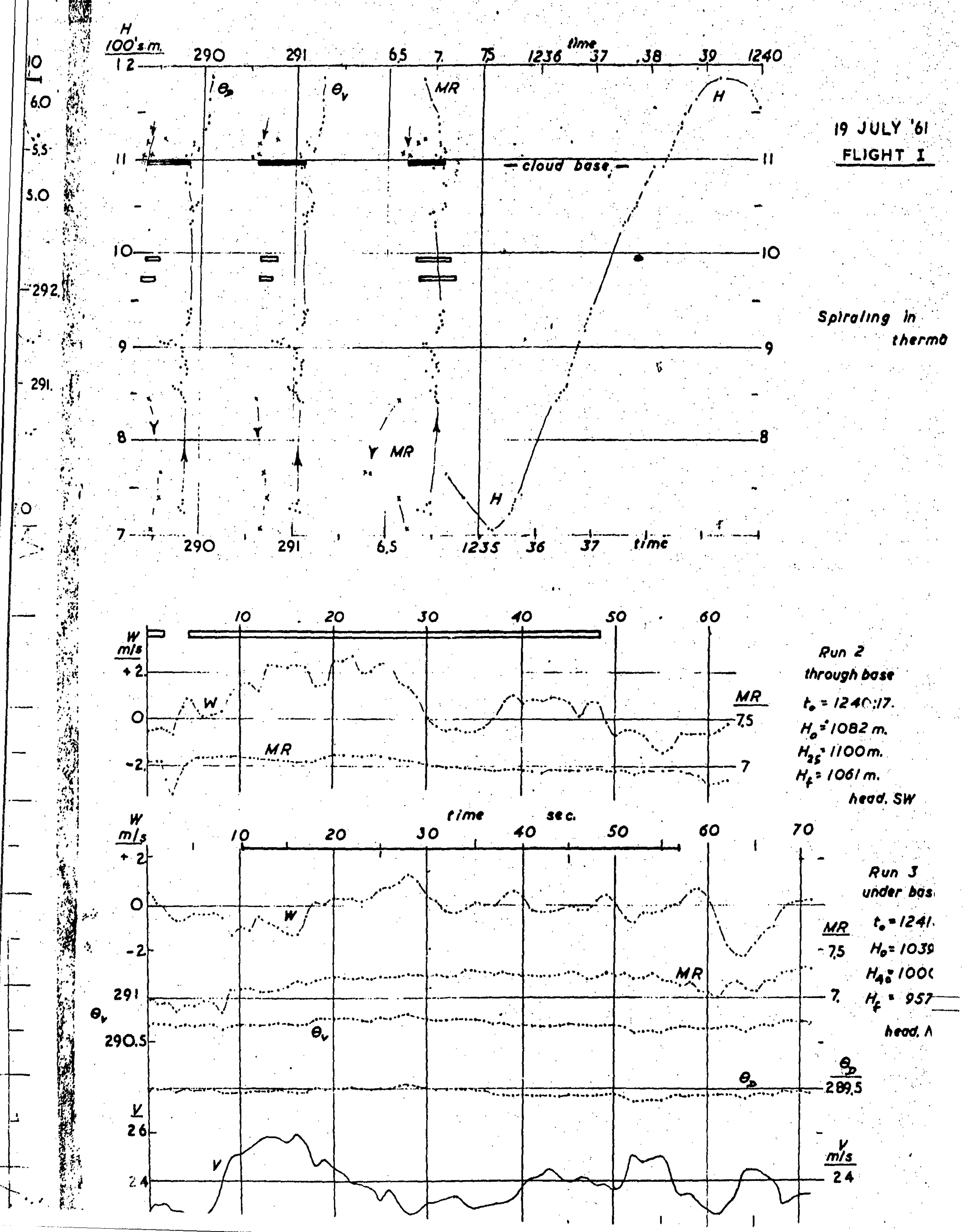
The soundings are similar to those obtained the previous day, i.e. unstable layer in lower few dozen metres, roughly adiabatic in middle level and stable, dry, layer near cloud base. The X's on the ascent sounding mark values obtained after the glider had released from tow. Cloud base varies about 50 metres. At 1150 m a pass was made, while on tow, under a cumulus and the values obtained are plotted. Temperatures from 800 to 500 m on the descent were obtained while spiraling in a region where there were no clouds above.

From 1235 to 1240 BST the glider spiralled up in a thermal. MR, θ_V and θ_D are plotted vs height and the height of the glider is plotted vs time. The X's denote values obtained just prior to entering, and after leaving, the thermal. The glider entered cloud at 1100 m and broke off the climb at 1190m. The slope of H vs time is fairly constant and indicates a rate of rise of 2.3 m/s. Since the glider was sinking about 1.0 m/s the air, in which the glider was spiraling, was rising about 3.3 m/s. The time taken for a 360° turn was 25 seconds which gives a turning radius of about 90 m.

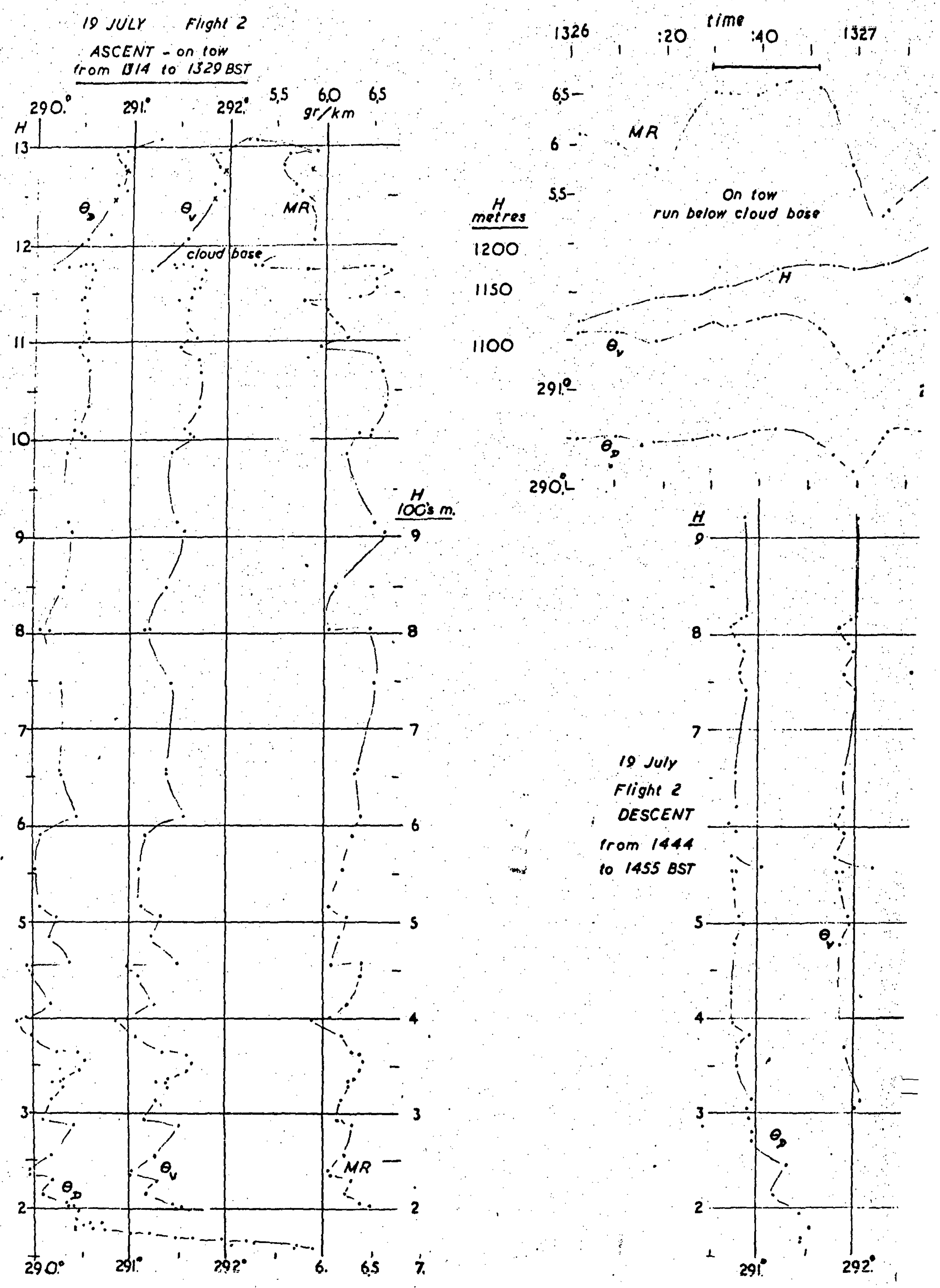
Runs 2 and 3 were made through the same thermal; Run 2 through the base, Run 3 under the base. At 1242 BST it appears that the thermal had risen well above the height of the glider; vertical velocities and temperature excess measured during Run 3 are negligible. This is one of the few cases where dryer air was not observed at the edge of the thermal. At 1242 BST it was noted that "edges of cu above are ragged but it still looks good under base". A minute and a half later the glider went back under the cu to search for lift but "only found small patch with max. of 2.0 m/s". The range of values obtained at this time are plotted at 975 m; the range of values obtained during Runs 2 and 3 are shown at 1090 and 990 m respectively.



19 JULY '61
FLIGHT I
Ascent - on tow
from 1217
to 1228 BST
θ_D, θ_V
°A
MR
gr/km
H
cloud
base
H
100's m.
On tow
Run at 1150m.
time
19 JULY
FLIGHT I
Descent
from 1244
to 1254 BST



19 JULY '61
FLIGHT I
Spiraling in thermo
cloud base
Run 2
through base
t_o = 1240:17.
H_o = 1082 m.
H_{25} = 1100 m.
H_f = 1061 m.
head. SW
Run 3
under bas
t_o = 1241
H_o = 1039
H_{40} = 100
H_f = 957
head. N
time sec.



19 JULY Flight 2
ASCENT - on tow
from 1314 to 1329 BST
290.°
291.°
292.°
5.5
6.0
6.5
gr/km
H
100's m.
θp
θv
MR
cloud base
1326
:20
time
:40
1327
6.5
6
5.5
MR
On tow
run below cloud base
H
metres
1200
1150
1100
H
θv
291.°
θp
290.°
19 July
Flight 2
DESCENT
from 1444
to 1455 BST
θv
θp

Fig. 10 19 July Flight 2

At the start of Flight 2 there was 4/8 small scattered cumulus, base 10 knots NE.

On the ascent sounding θ_D only is plotted below 200 m; $(t_D - t_W)$ was greater than 5.0°. A pass, made under cloud while on tow, is shown.

The descent sounding was made, from 900 to about 300 m, while spiraling in a downdraft.

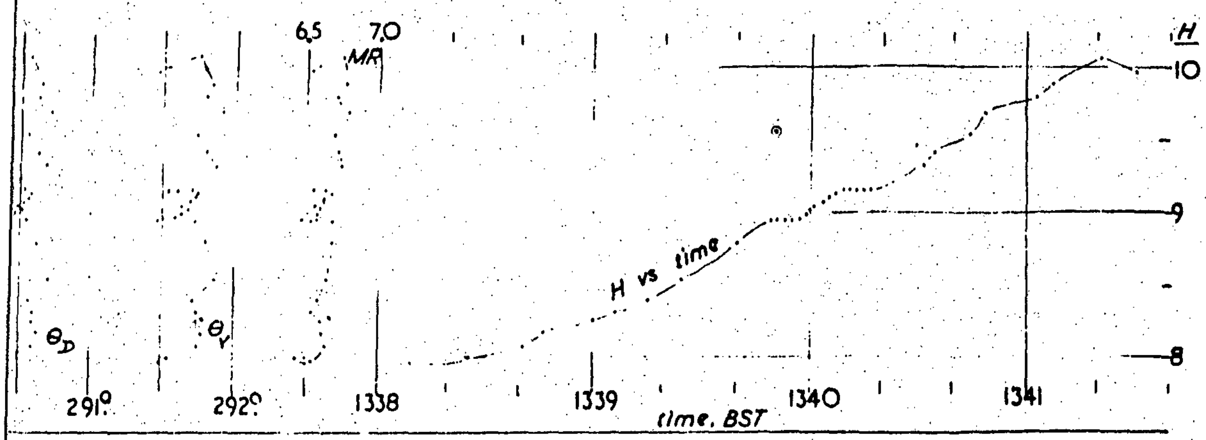
C 13

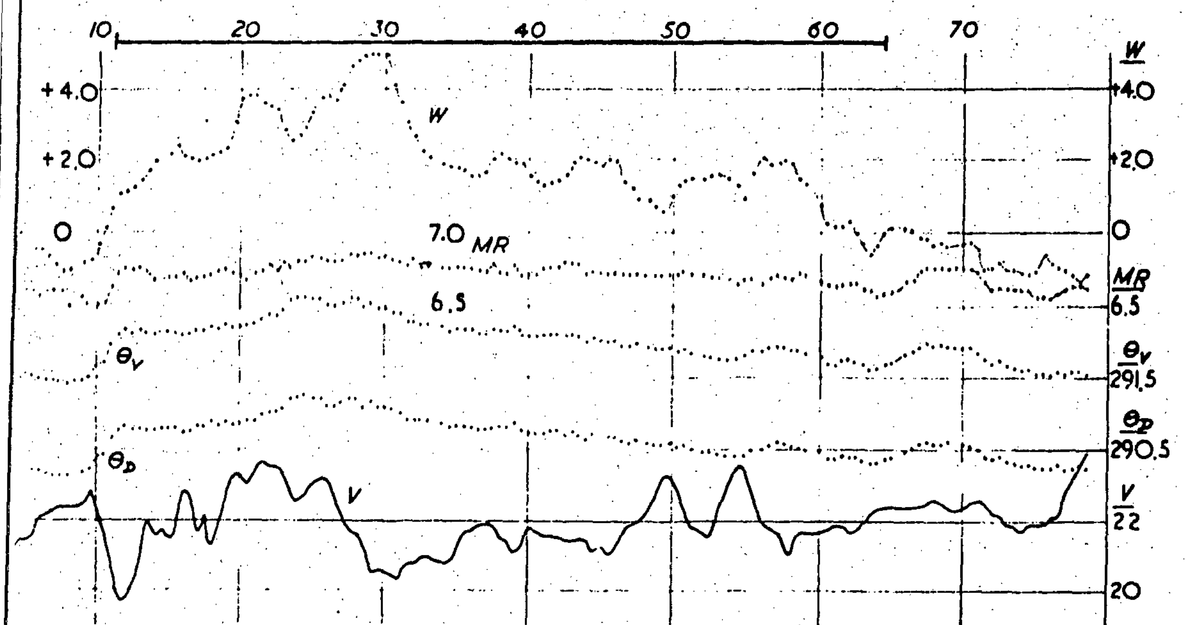
Fig. 11 19 July Flight 2 Runs 3,4,5,6.

At the end of Flight 2 the artificial horizon stopped due to a weak battery. When the runs were made the instrument was operating, however the conversion factor, C_A, appears to be different from that obtained for July 18. Analysis of attitude and vertical velocity changes indicate that C_V equals approximately 0.025. A value of 0.034 had been used for the machine computations; the appropriate correction was then applied, by hand, to the reduced values of W. This correction was not applied to the horizontal speed, U; therefore the airspeed, V, has been plotted for all runs.

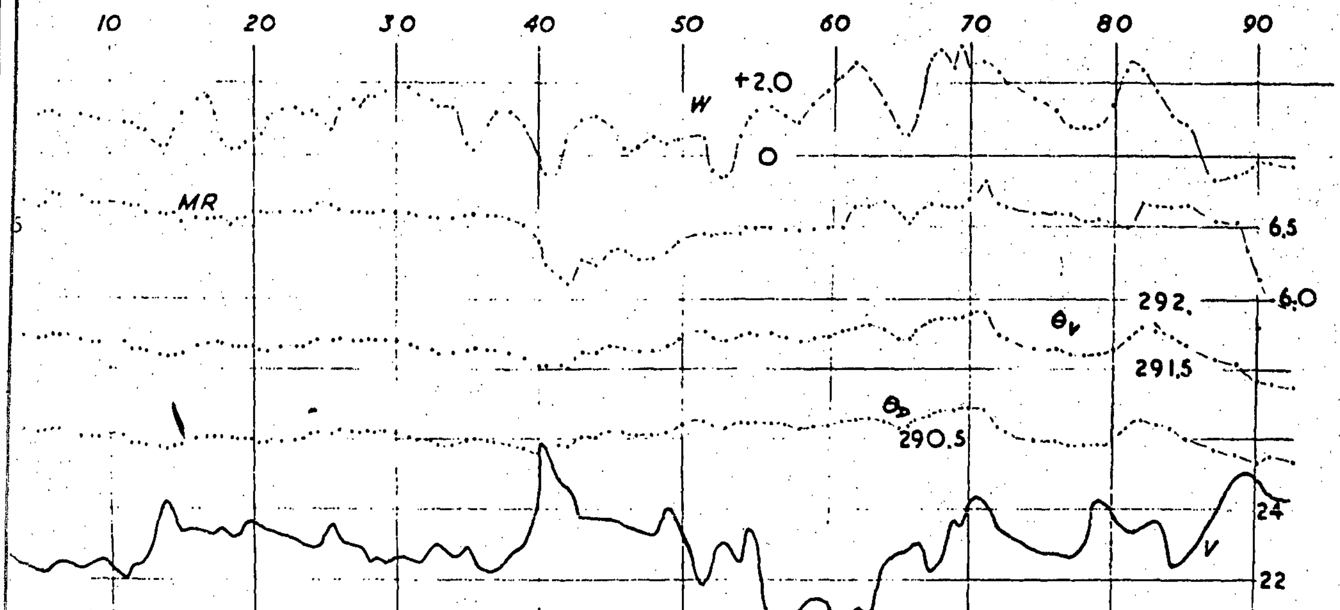
The sounding, in the upper left portion of the diagram, was made when the glider was spiraling in a thermal from 800 to 1000 m. The climb was made under a "line of cu running NE-SW". The slope, height vs time, and the scatter of temperature values indicate that the thermal was not properly centered. The achieved rate of climb for the 200 m is about 1.25 m/s; over shorter portions roughly 1.75 m/s was obtained.

The glider broke off the climb at 1000 m and then proceeded to make runs (nos. 3,4,5,6) under the line of cumulus. The data obtained indicates a group, or line, of thermals rather than an individual, isolated thermal. Vertical velocities tend to coincide with increased virtual temperature, e.g. Run 4 from t_s = 60 seconds to end. Run 5 indicates that the line is composed of two primary cells.

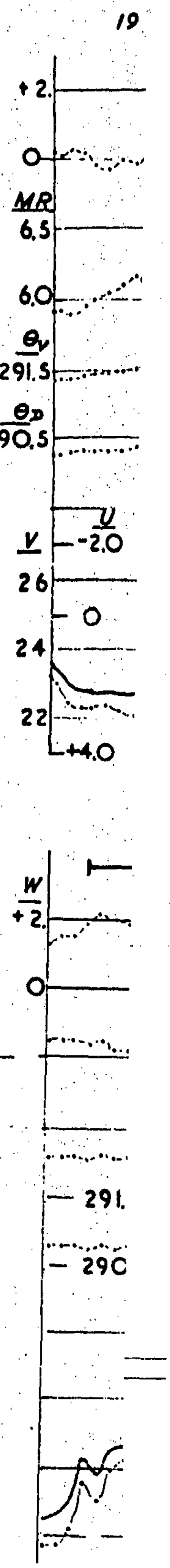




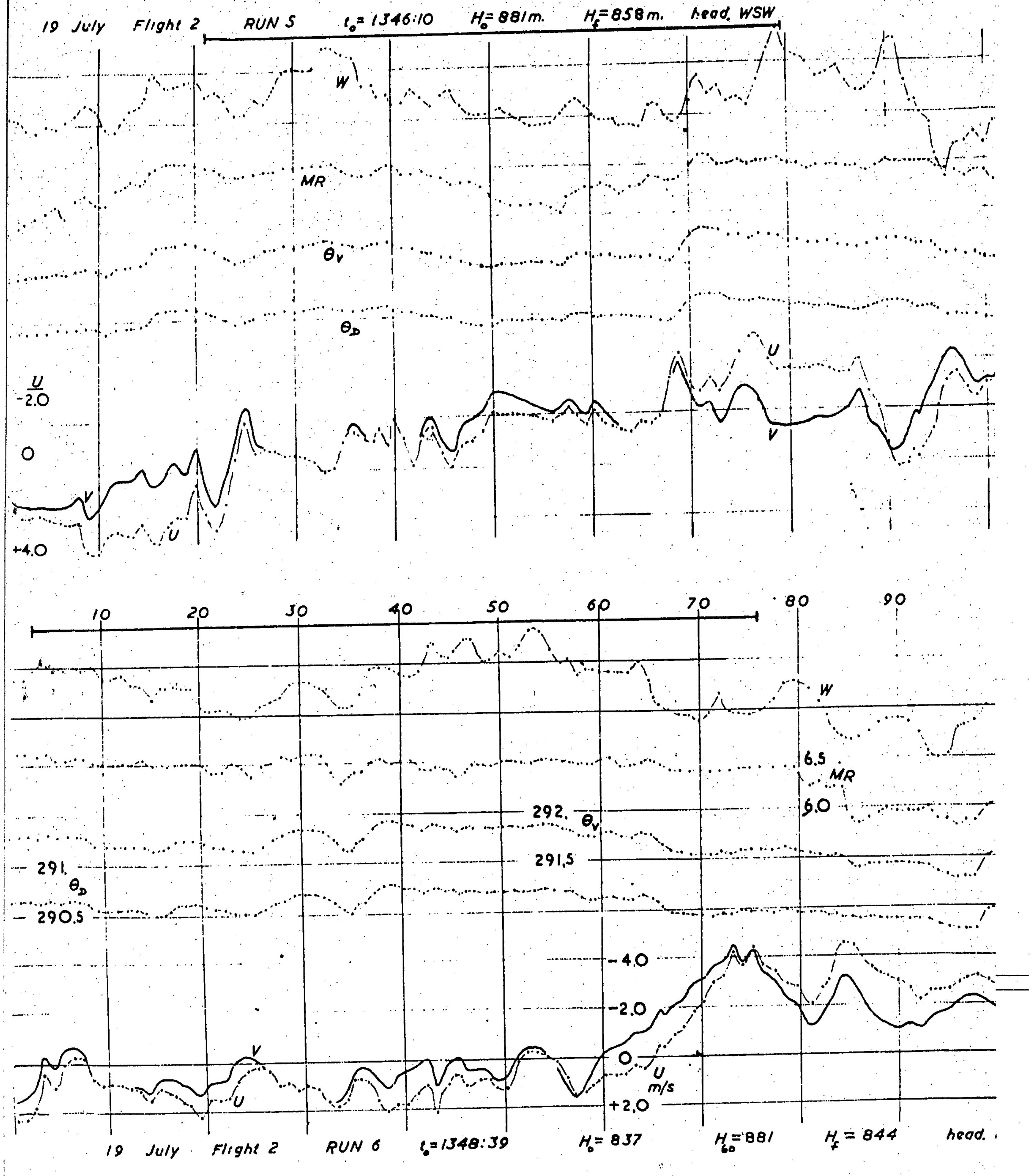
July Flight 2 RUN 3 t_o= 1342:00 H_o= 960 H_{40}= 1003 H_t= 992 m. head. WSW



19 July Flight 2 RUN 4 t_o: 1343:46 H_o: 942 H_t: 957 m. head. NE



19 JULY FLIGHT 2



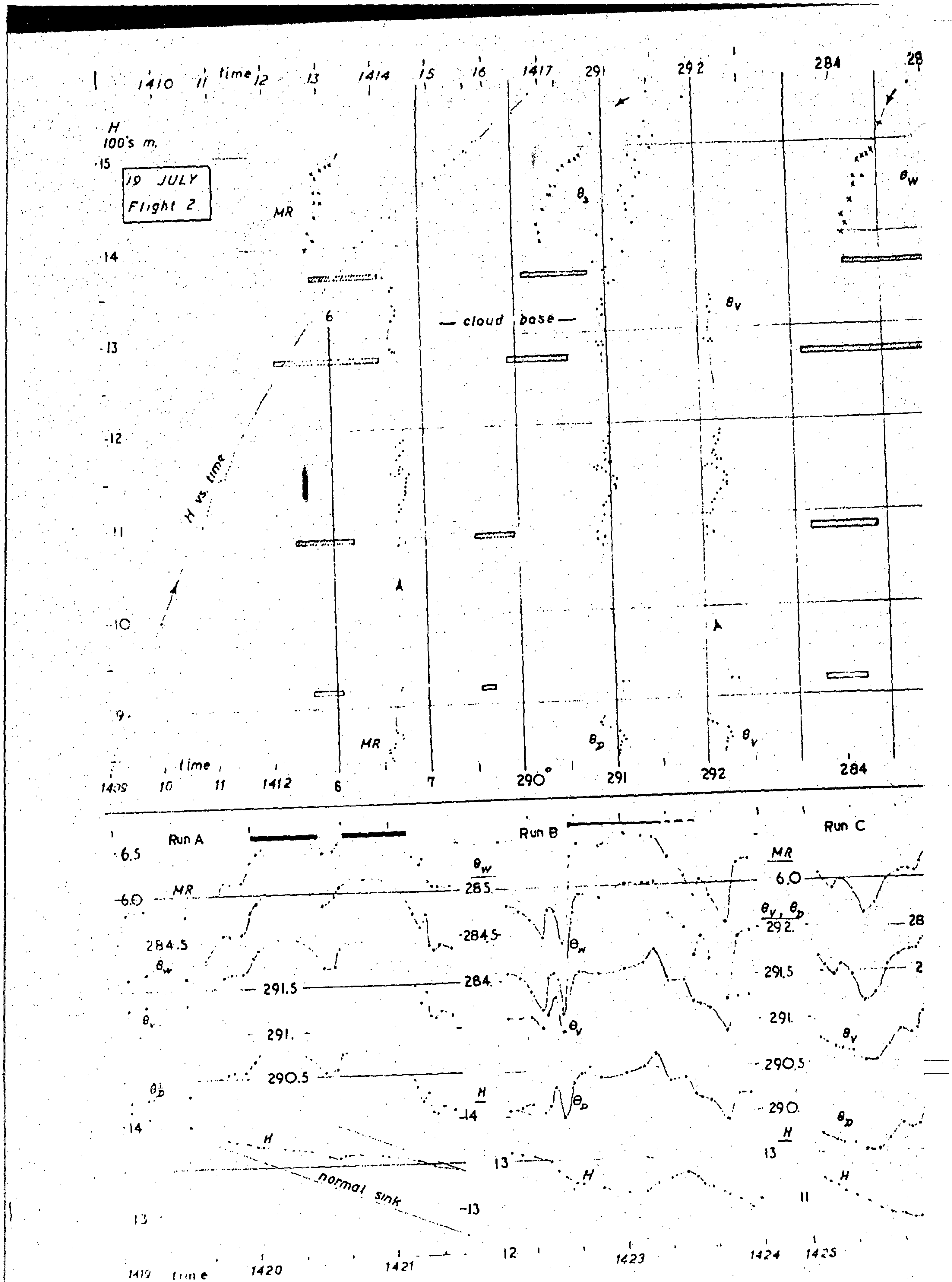

19 JULY
Flight 2
H
100's m.
time
H vs time
MR
θ_D
θ_V
θ_W
— cloud base —
Run A
Run B
Run C
normal sink
1410
1414
1417
1412
1420
1421
1423
1424
1425
290°
291
292
284
284.5
285
291.5
291
290.5
290
6.5
6.0

Fig. 12 19 July Flight 2

The figure opposite shows the data obtained when the glider was spiraling in a thermal from 840 to 1560 m. Cloud was entered at about 1320 m. Mixing ratio and potential temperatures are fairly constant below base; above base the lapse rate is between the wet and dry adiabatic (if one is to believe temperatures taken inside cloud). The crosses, X, indicate values of MR, θ_D and θ_W after the glider had emerged from cloud and was descending in clear air adjacent to it.

The graph of H vs time shows a rate of climb of about 2.8 m/s at 900 m, 2.2 m/s at 1100 m and 0.8 m/s at 1500 m.

Runs A, B and C are shown below the sounding. Run A was made through the cumulus at a height of about 50 m above the base. Because of the faulty artificial horizon and the fact that the camera was not running continuously (operated by hand) vertical velocities have not been plotted. A graph of height vs time and the slope of the normal sinking speed are shown.

Run B was made about 50 m below base and Run C about 250 m below. Vertical wind speeds, W, of 2 or 3 m/s were obtained below cloud on both runs. The range of values for MR, θ_D, and θ_W that were obtained during the runs are shown at their respective heights on the sounding. At 920 m the glider went under the cumulus again, four readings were taken and the range of these four are shown on the sounding. At this time only "patches of insignificant lift" were found.

The comparatively low temperatures that were recorded on these runs have probably been noted. The lowest value (289.55° during Run C) is 0.3° lower than any recorded on the ascent sounding 1 hr. 10 min. earlier and about 1.5° colder than those obtained when spiraling up in the thermal. These low values can only be obtained by evaporating the edges of the cumulus into comparatively dry air and bringing the mixture down 400-600 m. It must be assumed that the values of MR and θ_D, that were obtained in clear air above cloud base, are not typical of the air in which the cumulus edge evaporated. It is only by going back to the ascent sounding made on the first flight, about two hours earlier, that sufficiently low values of the mixing ratio (4.35 gr/km) can be found to account for the low temperatures.

Flight	Run	Thermal	Time	H	Diam., sec. vel.	θ,ΔR	cu	max. (2 sec.) θ_D	θ_v	r	Entry $\Delta\theta_D$	$\Delta\theta_v$	ΔR	Exit $\Delta\theta_D$	$\Delta\theta_v$	ΔR	max. w	min. W entry	exit	max. ΔU (or ΔV)
18 I	3	1	1127½	775	35	42	34	289.65	290.92	7.5	.20	.20	.20	.25	.35	.65	+2.3	-0.3	-1.0	-
18 II	2	2	1158½	925	-	27	20	290.1	291.4	7.3	*	-	-	*	.20	1.6	-0.1	-1.0	-1.4	-
18 II	2	3	1159½	900	35	37	15	290.55	291.9	7.5	.45	.70	1.3	.45	.70	1.3	+ 4.4	-0.5	-2.0	3.5
18 II	4	3	1202½	800	35	40	23	290.4	291.72	7.5	-	-	-	.30	.40	1.9	+4.2	-	-0.5	2.0
18 II	5	3	1204	760	-	-	34	290.5	291.3	7.45	.25	.25	-	.30	.40	.6	+2.3	-	-1.8	(4.0)
18 II	6	3	1206½	625	30	35	45	290.35	291.6	7.2	.25	.30	.35	.25	.25	.20	+2.2	-1.0	-1.4	3.5
18 II	7	4	1214½	425	20	20	-	290.95	292.25	7.15	.80	.95	.70	.60	.75	.30	+4.5	-1.4	-2.2	5.0
18 II	8	4	1215½	390	20	22	-	290.85	292.05	7.05	.60	.65	.70	.60	.60	.35	+3.4	-0.8	-1.4	3.5
18 II	9	5	1217	320	18	20	-	290.95	292.2	7.05	.70	.80	.60	.85	.87	.20	+3.5	-2.5	-	-
18 III	3	6	1259	1210	-	25	32	291.2	292.4	6.85	.15	.30	.90	.25	.50	1.6	+0.8	-1.2	-0.6	5.5
18 III	5	7	1302½	1030	40	40	-	291.15	292.4	6.95	.15	.30	1.0	.10	.30	1.5	+1.0	-1.4	-	2.5
19 II	3	8	1342½	1000	-	55	53	290.85	292.05	6.8	.55	.57	.35	.50	.52	.30	+4.9	-0.8	-1.1	(4.0)
19 II	4	8	1344	950	40	45	-	290.7	291.35	6.7	.25	.35	.50	.35	.45	.70	+2.7	-0.2	-0.5	(4.0)
19 II	5	8a	1347	875	40	50	58	290.6	291.77	6.57	.22	.32	.65	.17	.27	.50	+2.7	-0.2	-0.3	(4.0)
		b			40	45		290.67	291.82	6.52	.22	.30	.47	.27	.37	.35	+2.7	-0.4	-1.5	(3.0)
19 II	6	8	1349	850	50	50	73	290.75	291.9	6.55	.22	.20	-	.45	.50	.60	+3.0	0	-1.8	(5.0)

$* \ \overline{\theta}_{D_{in}} - \overline{\theta}_{D_{out}} \simeq -0.1^\circ$

SUMMARY OF RUNS

The table opposite summarises the values obtained during runs below cloud base. The maximum values of Θ_D, Θ_V, MR and W, and the minimum value of W, are not peak values but those which had a duration of at least two seconds. The delta values indicate the difference between 2 second minima and 2 second maxima.

The diameter of the thermal, determined from the velocity pattern, from the temperature and mixing ratio pattern and from the horizontal extent of the cumulus above, is given in seconds and should be considered an approximation only.

Comparison with isolated thermal model

One of the outstanding features of the model is that the vertical velocity in the centre of the thermal is about twice the rate of rise of the thermal as a whole; the air at the edge of the thermal is descending half the rate and the maximum horizontal velocities are roughly equal to the rate of rise of the thermal. (The difference in the horizontal velocities encountered by a glider would be twice the rate.)

Caution must be used when comparing the values in the table; the runs were made at various positions in the vertical (relative to thermal cap). If one chooses a run, e.g. 18 II 2 thermal 3, when it is believed that the glider was traversing the centre, both horizontally and vertically, then the velocities encountered compare favourably with the model.

On many of the runs there is a comparatively large difference between the minimum W encountered when entering the thermal and when leaving. Selecting those runs, both above and below base, when it is felt that sufficient time had elapsed on both sides, we find that in five cases the maximum downdraft occurred on the upwind side of the thermal, and on the downwind side in six cases. (The wind was 5-10 kts. and steer negligible.) On the other hand the maximum downdraft occurred when leaving the thermal in 8 out of 11 cases.

Another feature of the isolated thermal model is that it has a finite depth and that a region of outflow is found in the upper portion, inflow in the lower. We have two cases of inflow, 18 II 6, 18 III 3 (or three cases if 19 II 6 is included) which were obtained when it was confidently felt that the glider was in the lower portion. The two cases of outflow are not clear cut but it is felt that the glider was in the upper portion.

The formulae used to predict the behaviour of the isolated thermal and a nomogram are presented in the Appendix. Given any two values of $\Delta\overline{T}_v$, R or W_{cap}, the third may be determined. $\Delta\overline{T}_v$ is the average virtual temperature excess, R is the thermal radius and W_{cap} the rate of rise of the thermal as a whole. Any two quantities will also determine a value of "$k^{1/2}$" which remains constant throughout the life of the isolated thermal model. It is of interest to determine the approximate value, or range, of $k^{1/2}$ from the data obtained during the runs. The value may differ from thermal to thermal but it is reasonable to assume that this difference would not be great when comparing thermals over a given terrain in similiar conditions.

We are only justified in taking those runs where it is fairly certain that the glider traversed the approximate centre of the thermal, i.e. 18 II 2 and 18 II 7. The $\Delta\theta_V$ values given in the table are close to the maximum temperature excess. To establish the average excess it was arbitrarily decided to take the mean of $\Delta\theta_V$ from the entry and exit columns and divide by two. The radius, in metres, was obtained from a combination of the velocity, temperature and mixing ratio patterns. The rate of rise of the thermal, W_{cap}, was determined by taking one half of the 2-sec. maximum W.

These three quantities give three points on the nomogram. A single point was selected and the values at this point are given below.

run and thermal	H	from data $\Delta\overline{T}_v$	R	W_{cap}	from theory $\Delta\overline{T}_v$	R	W_{cap}	$k^{1/2}$	height of Z_{cap}	Z_o relative to ground
18 II2,3	900	.35	425	2.2	.32	400	2.5	90	1300	-450
18 II7,4	425	.42	230	2.25	.42	230	2.25	64	650	-420
18 II9,5	320	.42	220	1.8	.40	210	2.0	58	540	-450

Run 18 II 9 has also been included although the position of the glider relative to the thermal, both horizontally and vertically, is not known. The height of Z_{cap} has been determined by assuming the glider is in the centre of the thermal; the radius has been added to the glider's height. The height of the thermal above the theoretical point source, Z, is determined from the nomogram (Z = 4R) and the height of the point source, Z_o, relative to the ground is then established. (Height of ground is 150 m.)

Comparison can be made with data obtained from other runs, or from spiraling in a thermal, although additional assumptions must be made. On July 19, Flight II, runs 3, 4, 5 and 6 were made under "a line of cu"; it is therefore difficult to classify the thermals as isolated. On Run 3 there is an indication from the vertical velocities that there is a primary cell of 40 second diameter. By multiplying 40/2 by the average speed, $\bar{V}$, (22 m/s) a radius of 440 m is obtained. The average temperature excess and W_{cap} were determined by applying the same rules as above. The three values, surprisingly, give one point on the nomogram and a height of Z_o relative to the ground that is similar to the above cases.

run and thermal	H	from data ΔT_v	R	W_{cap}	from theory ΔT_v	R	W_{cap}	$k^{1/2}$	height of Z_{cap}	Z_o relative to ground
19 II 3,8	1000	.27	440	2.45	.27	440	2.45	86	1760	-420
19 II 5,8	875	.16	550	1.40	.12	500	1.70	82	(1500)	(-650)
19 II - 9	1250	.35	-	2.10	.35	260	2.10	65	1425	+225
" "	900	.40	-	2.60	.40	350	2.60	83	1250	-300
19 I -10	900	.35	-	2.30	.35	310	2.30	75	1200	-200

Two primary cells are apparent in Run 5. If we take each separately $\bar{\Delta T}$ is 0.15° for one, 0.17° for the other. The radius is the same (24 m/s x 23 sec. and 26 m/s x 21). W_{cap} is the same. It is necessary to adjust the values to arrive at a single point on the nomogram. If we assume that the thermal(s) is the same as the one(s) traversed about four minutes earlier during Run 3 then we cannot assume that we are passing through the centre of the thermal. Taking isolated thermal theory, the cap has risen about 500m in 250 seconds. The glider is 125 m lower; the cap is therefore 625 m above the aircraft. Taking Z=2000 m we arrive at a theoretical point source of 650 m below ground.

Even more assumptions must be made when comparing data obtained during spiraling in a thermal. Because the vertical velocities are greater than the rate of rise of the thermal the glider will climb relative to the cap. It will reach a point (dependent upon radius, W_{cap}, glider performance, etc.) that is roughly 0.8 - 0.9 times the height of the cap above the point source. It can maintain this relative position and will climb 0.8 - 0.9 times the rate of rise of the thermal.

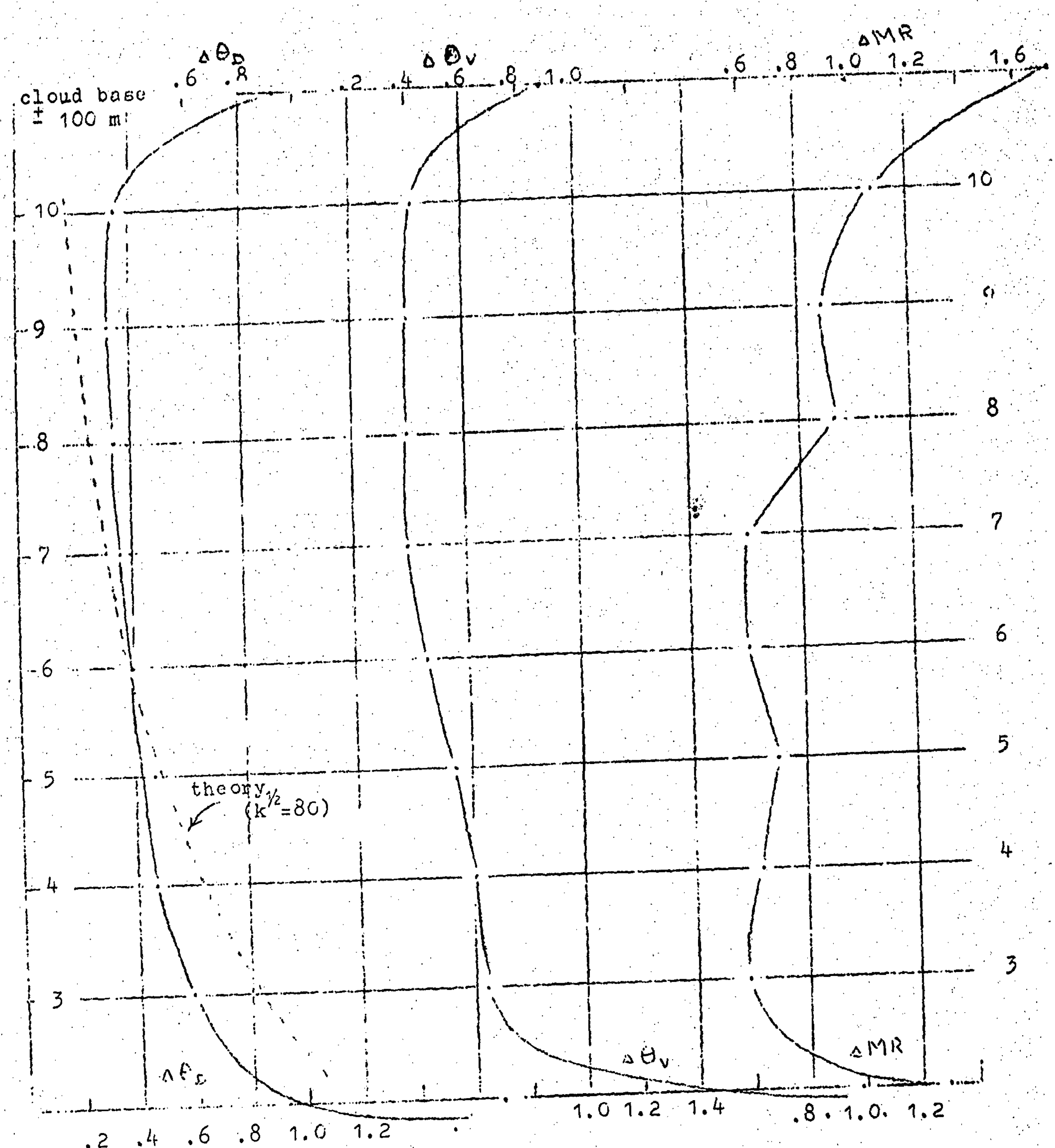
The radius cannot be obtained from the data . For thermal 9 above the temperature of the environment was not recorded prior to entering the thermal; it was necessary to estimate the average excess from the descent sounding and other data. Estimates made at two levels give a radius that is greater at the lower level, which is nonsense. Data for thermal 10 was also obtained when spiraling in a thermal.

Too many conclusions should not be drawn, especially from the latter group. It is surprising however that there appears to be such close agreement between the observations and the theory. Assumptions, out of necessity, have been made but the same "rules" have been applied to each case unless there was sufficient justification for not doing so.

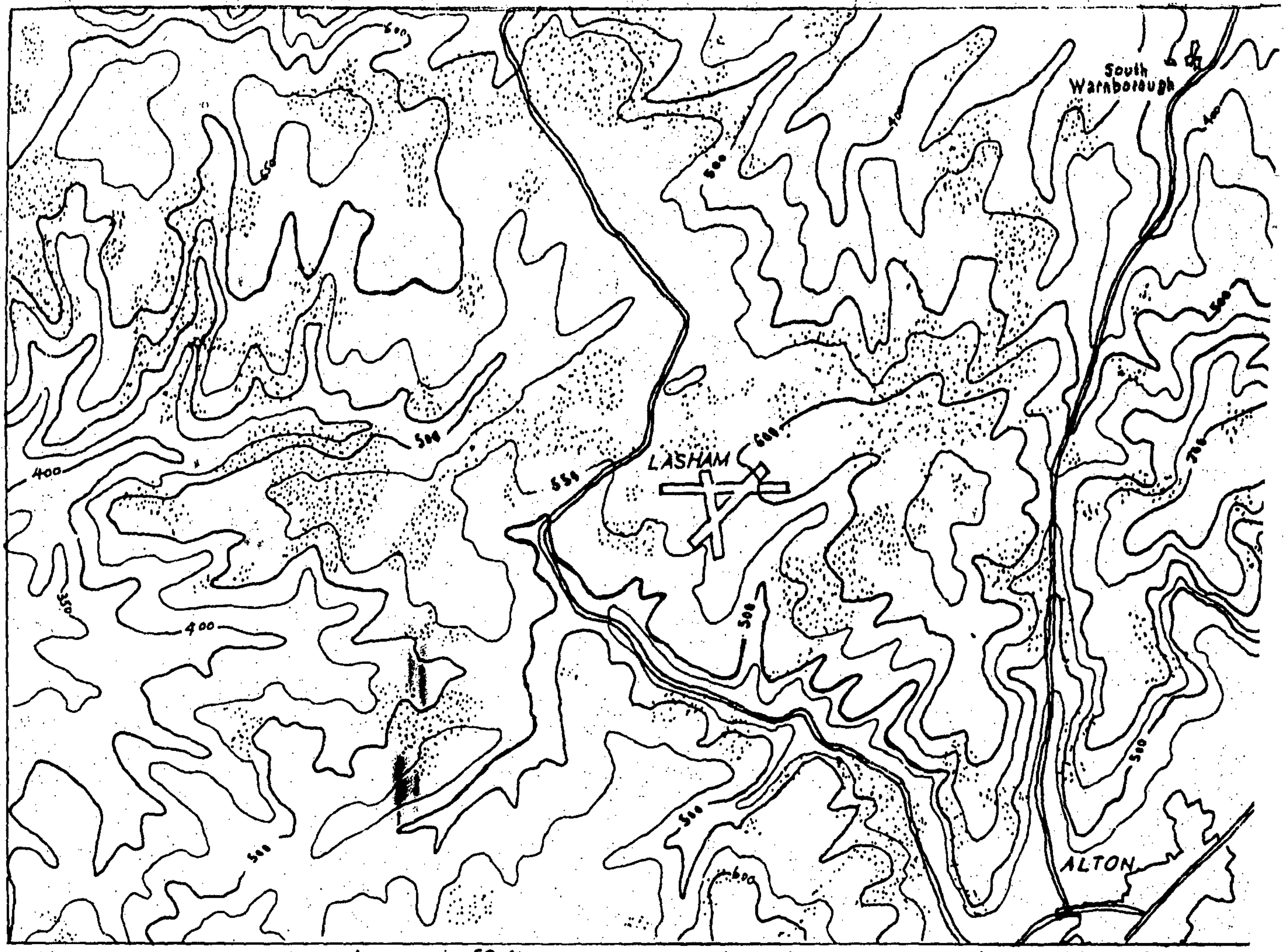
Additional computations were made to determine the change of temperature excess with height. The difference between the minimum and maximum values of θ_D, θ_V, and MR that were recorded in various 200 m depths were determined from the soundings and runs. The levels used were 200 - 400m, 300-500, 400-600, 500-700, ... 900-1100m and in addition ground - 200m, ground-250m, and cloud base $\pm$ 100m. Each sounding or group of runs was listed as one case. Averages were determined and the results are shown on the diagram. The number of cases are shown in parenthesis. If less than 4 or 5 points were recorded in any level on a sounding the difference between the values were not included. This method of determining the change of $\Delta\theta_D$, $\Delta\theta_V$ and ΔMR with height is based on the assumption that, during soundings, values are recorded both in and out of thermals. This assumption is not necessarily justified, however if enough cases are obtained it is of interest to see if any pattern emerges. As expected the greatest temperature differences occur in the ground layer; the increase of $\Delta\theta_D$ at cloud base $\pm$ 100 m is due to stable air above base, the high values of ΔMR in the upper levels are due to dry air above base and dry air that has descended from above the base.

The curve of $\Delta\theta_D$ is remarkably smooth. To compare this curve with isolated thermal theory a value of $\Delta T_V = 0.5^\circ$ at 500 m and a $k^{1/2} = 80$ were selected. The resultant curve (broken line on diagram) is drawn and indicates a greater decrease of temperature excess with height than the mean of the observed values.

The above computations and comparisons have been included in this report only to give an indication of how the data may be applied and some of the problems involved when comparing the observed values with those predicted from isolated thermal theory.

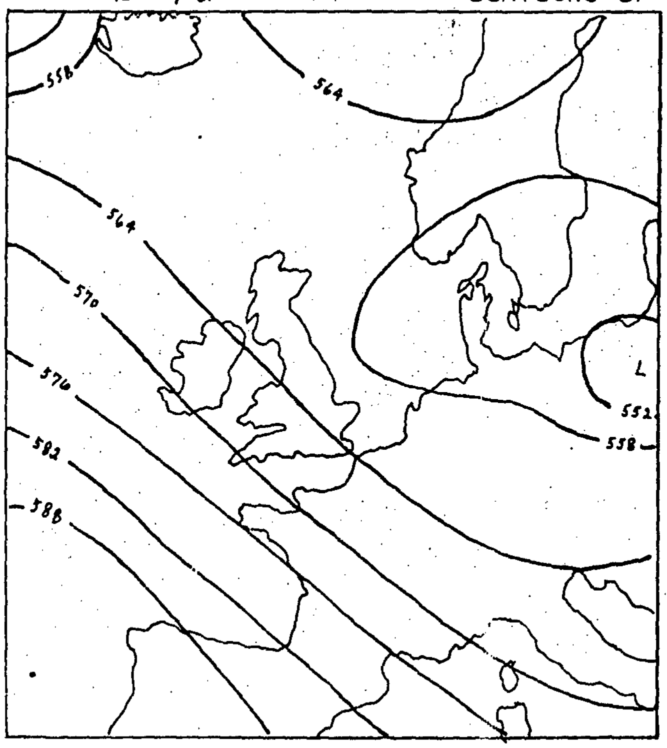


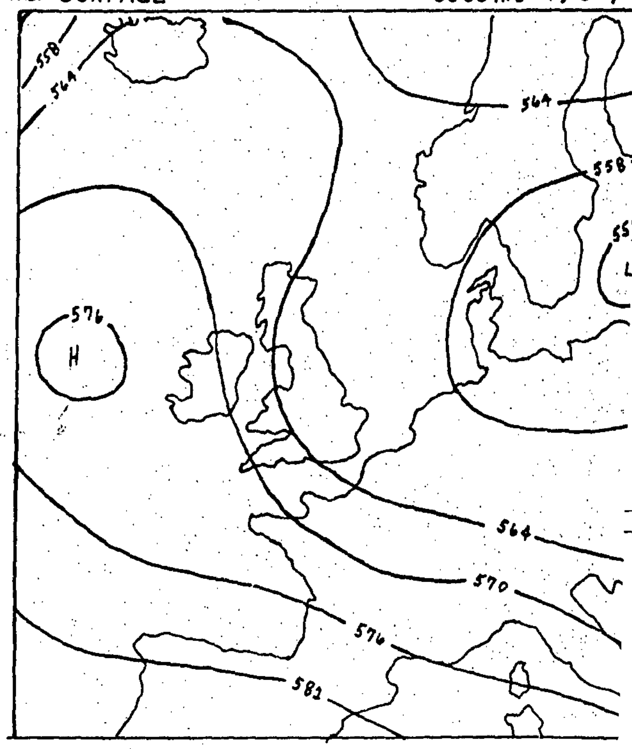
Ht. range, m.	$\Delta\theta_D$, °A	$\Delta\theta_V$, °A	ΔMR, gr/km
ground-200	1.507 (9)	1.840 (6)	1.050 (6)
ground-250	1.685 (10)	1.980 (6)	1.290 (6)
200 -400	.596 (11)	.634 (8)	.575 (8)
300 -500	.468 (11)	.611 (8)	.638 (8)
400 -600	.475 (11)	.552 (10)	.700 (10)
500 -700	.395 (9)	.451 (8)	.607 (8)
600 -800	.356 (11)	.395 (10)	.606 (10)
700 -900	.342 (9)	.400 (9)	.930 (9)
800 -1000	.323 (10)	.406 (9)	.895 (9)
900 -1100	.349 (10)	.412 (10)	1.080 (10)
cloud base ±100	.923 (10)	.890 (10)	1.728 (10)



contours drawn every 50 ft.   main roads   woods   1 inch = 1 mile

oooo hrs 18 July '61   CONTOURS OF 500 mb. SURFACE   oooo hrs 19 July





APPENDIX

Map of Lasham Area

Lasham Airfield is situated 1° 02½' west and 51° 11' north. There are several small villages in the area; Alton is the only town within 5 miles; Basingstoke lies 6 miles to the NNW. The wooded areas are shown on the map, the remainder primarily being cultivated fields.

Contours of 500 mb. Surface

The 500 mb charts for 0000 hours GMT on 18 and 19 July are shown. (Surface charts were not available at the time of compiling this report.) Dry bulb potential temperatures, mixing ratio, wind direction and speed at various levels are given for Crawley, the nearest station.

18 July 1961 1130 GMT

level, mb	θ_D, °A	MR, gr/km	Winds level	dir.	speed, kts.
998	293	-	998	340	06
937	292	6.8	900	350	10
900	-	6.1	850	340	15
850	294	5.2	750	330	08
805	-	4.1	700	310	14
778	295	4.2			
755	298	4.1			
736	302	3.3			

19 July 1961 1130 GMT

level, mb	θ_D, °A	MR, gr/km	Winds level	dir.	speed, kts.
998	292	8.3	998	010	03
995	-	6.8	900	360	10
984	291	6.4	850	350	08
925	291	5.9	750	350	10
859	292	4.8	700	350	07
846	294	4.5			
812	-	3.8			
783	-	3.6			

Nomogram of Isolated Thermal

Given any two quantities, one may obtain the following from the nomogram opposite:

R, metres, radius of isolated thermal (thin solid lines)

Z, metres, height of thermal cap above theoretical point source (same lines as R)

W_{cap}, m/s, rate of rise of thermal cap (dashed lines, slope -45°)

ΔT_v, $^{\circ}$C or $^{\circ}$A, virtual temperature excess (thin solid lines)

t, seconds, time of release from point source (dotted lines, slope $+45^{\circ}$C)

$k^{1/2}$, see equations below (thick solid lines, slope 1:3)

Use of Nomogram, example:

Given: R = 250 m, $\Delta T_v = 0.5^{\circ}$C

then Z = 1000 m, W_{cap} = 2.5 m/s, t = 200 sec., $k^{1/2} = 70$

The absolute values of Z and t are of no immediate use, e.g. Z is probably not equal to the height of the thermal above the ground. Let us suppose that the radius and temperature excess were measured at H = 800 metres and that we wish to know the height, ΔT_v, etc. 300 seconds later. Since $k^{1/2}$ remains constant throughout the life of the thermal we follow $k^{1/2} = 70$ up to t = 500. The average temperature excess would be 0.13°C, W_{cap} = 1.55m/s, R = 390 m., Z = 1560 m., or the thermal would have risen 760 m.

Formulae

The nomogram was constructed from the following formulae:

$$W_{cap} = C(g\bar{B}R)^{1/2} \qquad z = nR \qquad V = mR^3$$

where $\bar{B}$ is the average density $\div$ total density i.e. $\frac{T_v - T_v'}{T_v'}$

The constants, C, n, and m were determined from laboratory experiment to be 1.2, 4 and 3 respectively. So that $\bar{B}$ would be dependent upon the virtual temperature excess only, the surrounding temperature, T_v', became constant, a value of 290°A being selected.

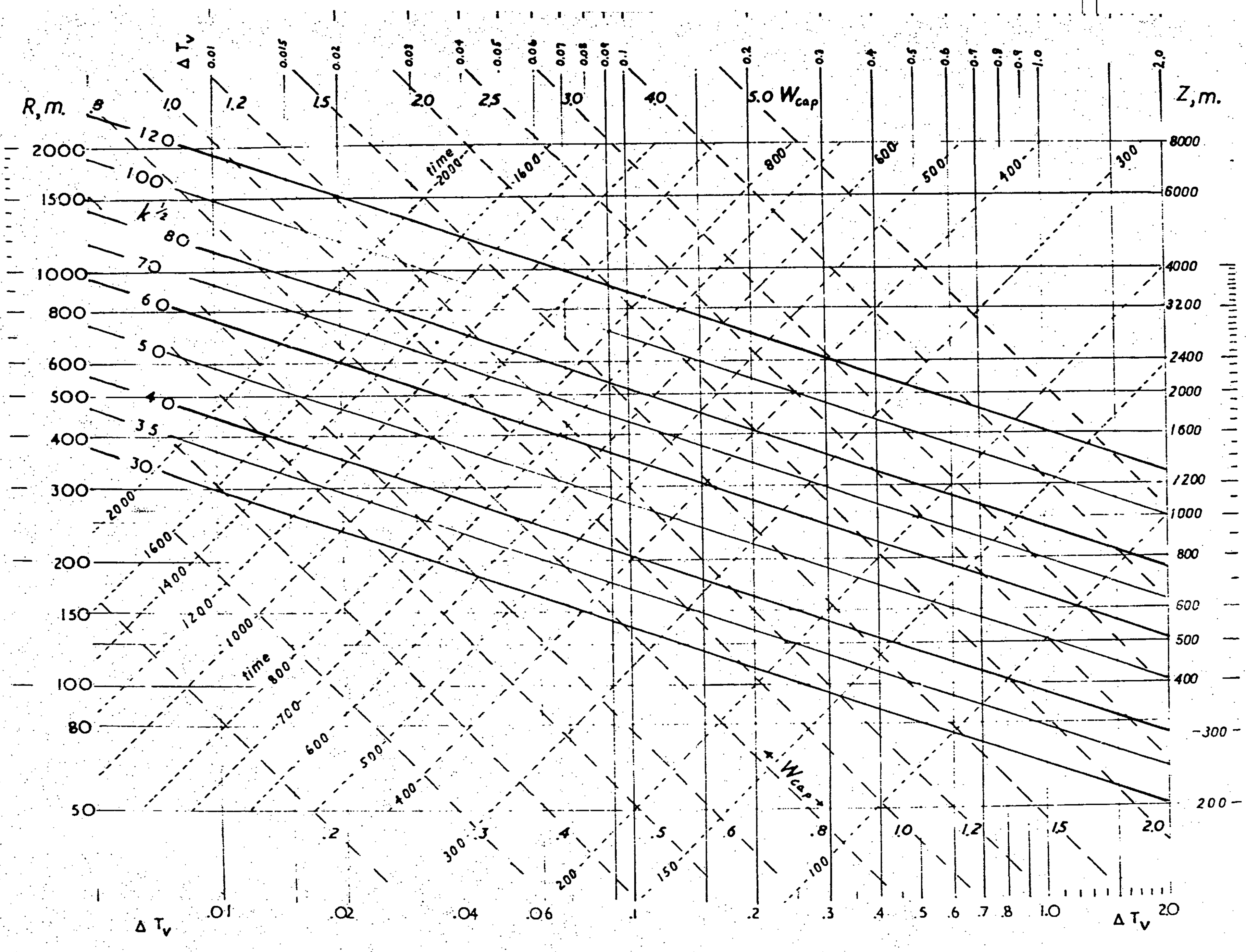
We may also write:

$$Z^2 = kt$$

and

$$k = \frac{2nC}{m^{1/2}} (g\bar{B}V)^{1/2}$$

where $(g\bar{B}V)$ = total buoyancy and is constant for any given thermal.



R, m.
Z, m.
ΔT_v
$k^{1/2}$
W_{cap}
time